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STUDY IN THE AREA OF SATELLITE METEOROLOGY. VOLUME I. MESOSCALE WEATHER ANALYSIS AND PREDICTION

Roy H. Blackmer, Jr., et al

Stanford Research Institute

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The basic research objectives were (1) to investigate new, long-range uses of geosynchronous satellite data and (2) recommend a system design to implement the satellite-derived meteorological data. This system is to be known as the Meteorological Information System (MIS). The purpose of MIS is to provide in-the-field weather support to the division and battalion echelons of the Field Army through a stand-alone analysis-and-forecast system utilizing only geosynchronous satellite observations.

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20 ABSTRACT (Continued)

The final report of this research is presented in three separate volumes:

Volume I - Mesoscale Weather Analysis and Prediction

Volume II - System Design

Volume III - Data Compaction and Image Display for Meteorological Satellite Imagery

The individual volumes complement each other regarding the objectives of the research study.

This volume (Volume I) is concerned with the uses of satellite data. Emphasis has been concentrated on four facets of geosynchronous satellite data utilizations: fundamental needs pertinent to analysis of visible and infrared imagery (including nephanalysis) temperature information from infrared radiometers, cloud-motion vector analysis, and software requirements for analysis and forecasting. In each of the studied areas attention has been given to anticipated data and display requirements. Identification of problem areas requiring further research is included.

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PREFACE

It is, of course, axiomatic that military operations benefit from knowledge of meteorological conditions. As the military weaponry and stratagems become more sophisticated, the need and variety of meteorological data also increases. A substantial organizational effort is devoted to satisfying this need. Eventually the acquisition and application of meteorological information currently for Army use will be dependent upon two sources: (1) the Air Weather Service (AWS) and (2) the proposed Automatic Meteorological System (AMS) of the Army itself. The Air Weather Service supplies weather information of a large scale to the Field Army and Corps. [Such large-scale (or synoptic) meteorology is derived through a network of stations not less than 200 km apart.] The Automated Meteorological System is planned to supply weather data on a small scale to the field units (primarily at the division and battalion levels). [This small-scale (or mesoscale) meteorology is applicable for an area that does not exceed several hundred kilometers on any side.] Thus, the Automatic Meteorological System is to have the responsibility (and challenge) for connecting the synoptic weather data to the mesoscale data as well as for providing for any new environmental information needed by the Army field units.

A recent Army study[1] has identified a number of environmental parameters that require improved observation and/or forecasting as well as some that are not yet available through existing capabilities. These parameters include, in part, surface pressure, pressure profile, surface temperature,

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[1]Tactical Environmental Support System (TESS), Appendix J, Requirements/Capabilities Summary, U.S. Army Intelligence Center and School, Fort Huachuca, Arizona (June 1973).

temperature profile, winds (surface and aloft), moisture profile, density profile, sky cover and ceiling, visibility, slant range visibility, trafficability, icing, and turbulence. Since the need for information on the foregoing environmental parameters in military situations ordinarily cannot be completely satisfied through in situ observation, it is natural to explore the possibility of using satellite observation as a possible remedy for these deficiencies.

A. The Meteorological Information System (MIS)

The Defense Meteorological Satellite Program (DMSP) is an Air Force Project relating to military utilization of satellite data. The activity of DMSP White Sands Missile Range is directed toward investigating how meteorological satellites could supplement the proposed automatic Meteorological System capability of the Army. In particular, the DMSP seeks (1) to solve meteorological problems of key military importance (such as fallout potential, target visibility, trafficability, reconnaissance probabilities) using earth-satellite sensors, and (2) to develop a system to implement the satellite-derived meteorological data for Army use. This system would be known as the Meteorological Information System (MIS). The basic objective of the Meteorological Information System is to provide in-the-field weather support to the division and battalion echelons of the Field Army through a stand-alone analysis-and-forecast system utilizing only satellite observations. The satellite data will be supplemented by local weather observations as recorded by division and battalion meteorological stations using automatic weather stations currently in use by the Army.

B. Elements of the Meteorological Information System

By DMSP definition the basic elements of the system would consist of an earth-synchronous satellite with receiving stations at the division and

battalion levels. The meteorological satellite will be a military space vehicle featuring SMS-type ground resolution and frame times. It is to be equipped with visible and infrared Spin-Scan Radiometers (VISSR) to generate good-quality imagery and will also carry a highly advanced vertical temperature profile radiometer (VTPR). The information flow of the system is sketched in Figure 1.

The Division Meteorological Stations (DMS) must be capable of being housed in a truck-trailer van outfitted with the required hardware and software to receive the satellite data (along with surface data from the Battalion Meteorological Stations), process these data suitable for analysis, perform the necessary analyses and forecasts using a variety of appropriate algorithms, display the data in a variety of forms for checking and amendments, and disseminating the verified products to the division and battalion levels. As conceived, the DMS van will be responsible for producing current status and weather forecasts over a 100-mile square area.

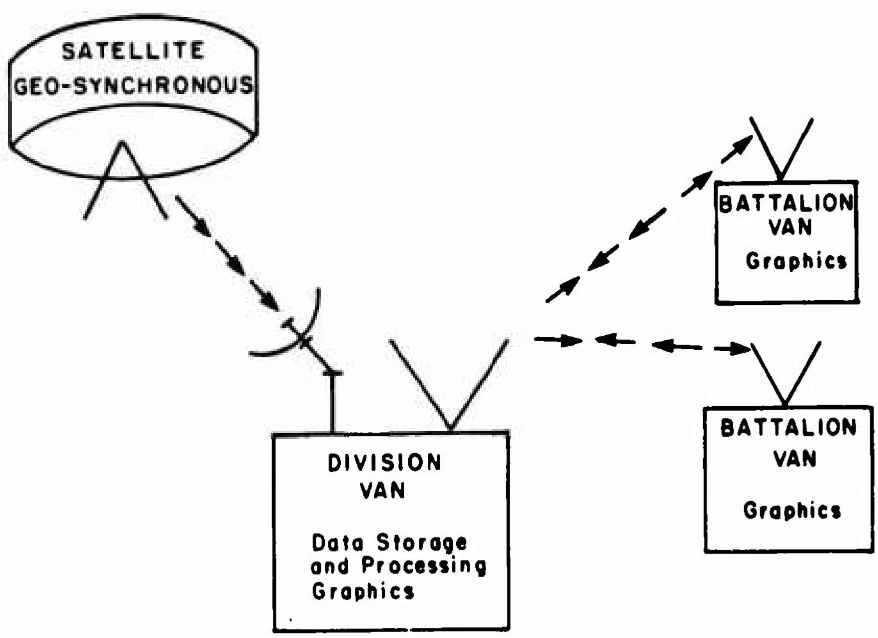

FIGURE 1 INFORMATION FLOW—MIS

The Battalion Meteorological Stations (BMS) will be a van equipped with sufficient hardware and software to receive the processed data from the Division Meteorological Station via a direct radio communication link, do such local processing as may be appropriate, and display meteorological products that support military needs at the battalion level. Typically, the BMS van will receive and display local conditions over a 50-mile square area, plus display of forecast conditions for periods up to 24 hours.

Of particular importance is the stipulation that no other data will be available to the MIS for weather analysis and forecast; in particular, no additional support is to be expected or required from the U.S. mainland or overseas weather centrals.

C. Research Objectives and Scope

The research undertaken by SRI is in support of the problem-solving tasks charged to DMSP. By mandate of DMSP, SRI's basic research objectives were (1) to investigate new, long-range uses of satellite data rather than attempting immediate performance trade-offs and (2) to recommend a system design to implement the satellite-derived meteorological data to be known as the Meteorological Information System (MIS). Although some man-machine analysis was deemed allowable, the emphasis and goal of the design was to be as fully an automated meteorological information system as possible.

D. Results

The final report under this contract (DAAD07-73-C-0317), titled "Study in the Area of Satellite Meteoroiogy," presents the result of this research and consists of three volumes:

Volume I - Mesoscale Weather Analysis and Prediction

Volume II - System Design

Volume III - Data Compaction and Image Display for Meteorological Satellite Imagery.

Volume I is concerned with the research into the uses of satellite data. However, the scope of the effort was limited so that the principal emphasis has been concentrated on four facets of the satellite data utilization: fundamental needs pertinent to analysis of visible and infrared imagery, radiometry, automated cloud tracking, and software requirements for analysis and forecasting. Volume II presents the details of a conceptual design of the Meteorological Information System capable of utilizing meteorological data gathered by satellite for Army field operations. Volume III considers a wide spectrum of analysis aids and data processing procedures that can be employed, particularly with regard to cropping and verification, data compaction or enhancement, and methods of display and dissemination. While each volume is complete within itself regarding the specific tasks addressed, the individual volumes are intended to complement each other regarding the objectives of the research study.

CONTENTS

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ILLUSTRATIONS

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TABLES

I METEOROLOGICAL ANALYSIS OR DIAGNOSIS

A. Definition

Meteorological analysis diagnosis involves identification and interpretation of all data and processes necessary to reach the best possible statement of the present and future state of the weather or elements thereof. To make such an analysis using only satellite-observed data involves answering questions regarding the utilization of the kind of data generated as much as it involves deriving new processes by which meteorological analyses are made. Certainly before satellite data can be deemed useful for the Army, it must be determined: (1) that a required parameter can be "sensed" directly or indirectly via satellite, (2) that the parameter can be handled in the mesoscale dimensions needed by Army field operations, and (3) that the parameter information can be collected, analyzed, and reduced to a militarily-useful product, and disseminated, all in timely fashion.

B. Data Considerations

The observational data available for analysis are the MIS imagery and such profiles of the atmosphere that may be gleaned from the vertical temperature profile radiometer, plus the important characteristic of frequent observation from a stable viewing platform. Past experience with earth-synchronous satellite systems have pointed up the value of such frequent observations.

The description of mesoscale meteorological conditions is a difficult task, at best, even with the maximum data base available--to do so using satellite-observed data alone is an even greater challenge.

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The phenomena to be sensed include:

Visible and Infrared Imagery	Multispectral Radiometer
Cloud organization	Surface temperatures
Cloud type	Cloud temperatures
Cloud amounts	Water vapor
Terrain	Atmospheric temperature profiles
Water bodies	
Snow cover	
Relative brightness	
Relative temperature	

These basic data will then be subject to processing, using nephanalysis, radiometry, cloud tracking and numerical analysis techniques (singly or in concert), to yield useful information on such fundamental meteorological parameters as:

- Cloud cover
- Wind conditions
- Pressure
- Temperature
- Humidity
- Stability
- Precipitation
- Visibility.

C. Information Potential from Data Analysis

Some types of information that can be gleaned through analysis of the satellite data and their expected role in the analysis process are as follows:

1. Cloud Field

The analysis of cloud fields, through interpretation of pattern, type, and displacement, will play the fundamental role in assessing the

prevailing weather situation and act as a check on the credibility of the predicted weather situation. In making this analysis, the analyst will draw upon the visible image, the radiometric information, and the ground reports. As part of this analysis, the cloud field, through static presentation or time lapse, will have to be inspected for qualities important to diagnosis, such as:

- A demarcation of those clouds depicting a vortical structure or a band commonly associated with frontal activity--supplemented by an estimate of the state of development and those areas likely to be precipitating.
- Identification of thunderstorm or potential thunderstorm activity.
- A demarcation of those areas showing limited convective activity or definite thermal stratification (fog or stratus).
- Estimates of cloud base and heights through inspection of the radiometric data.
- Relative motion of clouds and/or rate of development.

2. Wind Field

Time lapse will aid in the basic determination that there may be multiple cloud levels. The sense of the motion at any given cloud level is a good substitute for the wind field and will be used by the analyst as such. A computer program, if it is capable of differentiating multiple cloud levels, will be used to specify the exact magnitudes of the motion. The result of this analysis should be available to the analyst as an overlay to a cloud picture or recalled for a display over the cloud picture on a cathode-ray tube to permit cross-checking the credibility of the motion analysis. If approved, the motion analysis is stored for use in other programs. The time-span over which such motion analysis is applicable cannot be stated with certainty--there are times when only an hour span will be required; other situations may call for a 3- or 4-hour span. However, if the time-span becomes too great, the motions

generated are more truly trajectories than streamlines but there may be situations when this parameter is desired. Flexibility in the computer programming seems to be the rule.

The limited number of cloud motions previously acquired will be used as input to a program which, through interpretation, generates an estimate of the wind field in cloud-free regions. This generated motion field should be brought up for visual inspection by the analyst and amended as desired, then restored. It is understood that motion analysis is based on series of vectors, but it is probable that it is more efficient to restructure the vectors to some evenly spaced grid than to display it as a streamline. The wind field, as such, will be major input to the prognostication of the wind field. It is also imperative that the prognostic wind field be available for recall and perusal prior to dissemination. Also, prognostic data on winds will help in the cloud classifications that are required for retrievals for partly cloudy conditions.

3. Pressure Field

There is nothing in satellite data that yields the pressure field specifically. However, an estimate of relative pressure organization can be gleaned from the wind circulation and cloud field. The cloud motion field will be used as basis for visual analysis of the prevailing broad-scale circulation--principally vortices and regions of convergence and divergence (high-pressure centers are usually cloud free over land).

4. Thermal Field

The analysis of the horizontal thermal field at the surface will be based on radiometric data. This requires a fairly detailed presentation of the surface temperatures displayed such that it can be superimposed over the cloud and wind data. Generally this field will not be

complete, due to interfering clouds. A program to interpolate this data over a prescribed area would be of value. The resultant analysis would be stored for prognostic use. Again the prognostic field should be available for recall by the analyst for checks on quality and completeness.

The vertical thermal structure will depend on an analysis of the vertical temperature profile data. In using this data the analyst should have the ability to specify those locations and frequency for which such data retrieval is desired. This will vary with the weather situation. In addition it may be valuable to have the ability to display a number of these retrievals on a common background. Although a number of channels (eight) will be routinely collected, only a few (two or three) may contain the data desired at some given moment. The manner in which the retrieved data are displayed is wide open for innovation. Experience indicates that the human has only a limited capacity to interpret multiple imagery--and then such imagery must be well differentiated. Thus the inspection of rain data or the result of computer processing must be reduced to a presentation of limited complexity.

5. Moisture Field

Most of the quantitative information on moisture will be drawn from the vertical temperature profile radiometer data. Consequently the foregoing comments remain applicable. It is an important meteorological parameter, however, particularly in the determination of the likely band of precipitation amounts. It is also important in the prognosis of cloud cover.

6. Stability

Visual diagnosis of stability is based on the absence of clouds or, conversely, the texture and organization of clouds. It is probably this aspect of the problem that will require the best possible resolution

since much emphasis is placed on cloud size, texture and spacing, particularly of low-level clouds and these are generally of small scale. Some help in determining stability is expected from the vertical temperature profile radiometer data if adjustment for interfering clouds in partly cloudy conditions can be dealt with successfully.

7. Precipitation

Currently, the specification of all precipitating areas has been only partially successful. Experience suggests that thunderstorms with brilliant white tops have a high likelihood of precipitation. Thus the ability to study the brightness of satellite data through "slicing thresholds" or radiance may be helpful. Again, strong reliance will be placed on radiometric data using selected windows for evaluation. The analyst should have the ability to investigate areas of choice in some detail and with changing resolutions, perhaps. The prognostication of precipitation will be of crucial importance to the military. Depiction of these areas on products disseminated to the command levels is most necessary.

D. Data Formats

The next step in the analysis process integrates these analyses into useful data bases for supplying information of key military interest. These are the tactical and strategical applications--viz, determination of nuclear fallout zones (friendly or hostile), target visibility for attack vehicles, ballistic winds, and weather data permitting reconnaissance (friendly or hostile) by light aircraft.

The capability of the satellite to capture certain meteorological parameters does not ensure automatically their full relevance to the Army. Such data must be processed into products or formats that are suitable for decision-making at the strategic and tactical levels. These include (but

are not necessarily limited to) hardcopy photographs, copies of annotated displays, numerical printout, and teletype communication messages. It is the responsibility of the analyst to be cognizant of the specific format needs of the field user if the Meteorological Information System is to achieve its full potential.

The types of user formats required by the Army are myriad, indeed, and at this time it seems to serve no useful purpose to attempt to describe a comprehensive list. The overriding qualities of the format should be an assurance of timely and accurate information with a minimal risk of misinterpretation. This would seem to require maximum concern for the way in which the user utilizes his information and a concern for clarity and simplicity consistent with the avenues of dissemination. The examples of key military interest previously mentioned can serve as a basis for the discussion of formats, viz:

(1) Fallout analysis--One type of end product at the tactical level that can be envisioned is a black-and-white map showing the hazardous fallout zones as defined in the Army Manual TM3-210. In addition, a desired end product would be a listing of the winds used for the fallout prediction.

(2) Another of the major field problems is the ability to predict target visibility using meteorological satellite data. Such data play a crucial role in aiming, guiding, and homing attack vehicles (airplanes and missiles) to the target area. In particular, visibility data are needed in the microwave, infrared, and optical regions. The desired end product in this case could consist of a series of probability values regarding target acquisitions in each of the modes that give the field commander the ability to exercise an option.

(3) A major problem is to determine and predict the meteorological influences on the trafficability of the ground as it affects Army operations, particularly troop movement and the movement of vehicles which can range from light to extremely heavy. The end product will probably be in the form of a map (black and white) on which the boundaries or regions of scaled trafficabilities are superimposed.

(4) The problem of securing weather information for reconnaissance decisions is probably the one most amenable to use of satellite data. It is primarily one of determining current and future cloud cover (amount and height) and surface visibility conditions. Again the end product is likely to be a map showing probabilities of given events--amount of cloud cover, height, type of cloud, and surface viewing conditions, especially if obstructions to visibility are present.

E. Analysis Needs Pertinent to System Design

Certainly for the benefit of the meteorological analysis, the Meteorological Information System should exhibit four characteristics that seem fundamental to its success:

(1) It must be able to present the analyst with "quality" meteorological information in terms of processing ability. Good analysis procedures will change with the addition of new meteorological knowledge--the ability to amend or substitute new programs or procedures also will be required. This also involves the capacity to have as good a data bank as possible in storage at all times to minimize the effect of data interruptions and, the corollary, to have the ability to regenerate a data bank if circumstances dictate.

(2) It must be able to assimilate, digest, and output the information with minimum "time degradation." Meteorological information is a product that spoils quickly--particularly, information focused at a specific point and time.

(3) It is important that the display capability be varied and interactive with the analyst (i.e., information could be added, deleted, or changed through the use of a light pen or other such device). It must be capable of multi-image display and subject to minimal misinterpretation through the use of distinct colors or symbols. Also, one of the elements in the diagnostic process is the ability to analyze and predict on a variety of scales--and the system must be flexible enough to permit this--at least to a reasonable degree.

(4) It must allow the meteorologist to play a role at all stages in the Meteorological Information System--in terms of his ability to override all stages in the system (from collection through processing to forecast) to check for quality and timeliness.

To fully exploit the Meteorological Information System, the meteorologist will have to have advanced training in satellite meteorology and have to be familiar with literature (cf. Anderson et al., 1969)[2] relating satellite data to other meteorological parameters. Undoubtedly the most relevant progress will come about through a vigorous research program by the Army itself.

F. Remarks

The basic requirements to meet the idealized purpose of the MIS are:

(1) Adequate data bases, utilizing only SMS imagery (taken in visible, infrared, and microwave domains) abetted by a profile radiometer and a minimum of local surface data.

(2) Choosing processing hardware and algorithms (plus man-machine interface) capable of data analysis.

(3) Selection of proper forecasting methods and/or models that yield the best results from the reduction of satellite data.

(4) Techniques for depiction of data in formats and ways that provide the most information and risk the minimum amount of misinterpretation by the meteorologist and the field user.

To achieve the data products listed above, it may be necessary that certain observations be received or certain processing done that may not be of immediate application. For example, the military may require a

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[2] R. K. Anderson et al., "Application of Meteorological Satellite Data in Analysis and Forecasting," ESSA Technical Report NESC 51, September 1969, with Supplement No. 1 in November 1971, and Supplement No. 2 in March 1973, U.S. Government Printing Office, Washington, D.C. (also issued as Air Weather Service Technical Report No. 212).

specification of rainfall duration and intensity, but before this answer can be reached, the satellite data itself, or the processing of it, will have to yield antecedent interpretation concerning available moisture. In the case of pressure specification, knowledge of the convergence or divergence of mass will have to be forthcoming from the processing of radiometric and wind data. Rectification of sequential cloud pictures is an important processing requirement before any analysis can be done. Thus there are sensing and/or processing needs over and above those of merely being able to observe some meteorological phenomena. These needs will vary with the meteorological phenomena being considered and it will be a major part of some future research effort to establish the degree to which the military needs can be met through satellite data. In this regard, studies of atmospheric energetics on the mesoscale (10^0-20^2 km) and numerical prediction of same are in immediate need.

Sections II through V of this volume describe the studies made in nephanalysis, radiometry, cloud tracking, and numerical prediction as they may apply in the Meteorological Information System. These studies are by no means the full and complete answers to the meteorological analysis and prediction problem but do point the way to future work.

It is not likely that the conceptual design will obtain its full validity until each of the basic requirements is fully researched, nor can the meteorological capability and technical practicality of the conceptual design be proven. The overall value of the Meteorological Information System will be judged by the success with which it can deal with these problems. Consequently follow-on work is recommended. These recommendations are given in Section VI.

II NEPHANALYSIS

A. Definition

The purpose of this section is to outline the manner in which meteorologist and computer might treat satellite data to obtain a useful nephanalysis. In this section the term nephanalysis will have a somewhat different meaning than is given in the "Glossary of Meteorology."[3] In the glossary nephanalysis is defined as "the analysis of a synoptic chart in terms of the types and amounts of clouds and precipitation." In this section the basic change in definition will be to replace the term "synoptic chart" with "satellite photograph" and delete the work "precipitation." This revised definition will correspond more closely to current usage of the term in the field of satellite meteorology. Nephanalysis in the satellite field consists mainly of reducing satellite pictures to line drawings for simplicity in transmission via facsimile circuits. These line drawings (see Figure 2) give boundaries of regions of various types of cloud cover (or clear areas) together with notations concerning type, altitude, and to some extent, amount of cover (MCO = mostly covered, MOP = mostly open). Figure 2 shows that this type of nephanalysis is complex and would be difficult to incorporate into a computer prognosis system. What is required is a nephanalysis scheme that will extract those data required for the diagnosis and prognosis tasks that are pertinent to the needs and objectives of the U.S. Army MIS.

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[3] "Glossary of Meteorology," American Meteorological Society, R. E. Huschke, ed. (Boston, Massachusetts, 1959).

FIGURE 2 CONVENTIONAL NEPHANALYSIS

B. Available Information

It is assumed that high resolution visible and infrared photographs from a geosynchronous satellite will be available to the meteorologist at frequent intervals during daylight hours and that nighttime IR photographs will be available at a similar frequency so that 24-hour surveillance of the cloud cover is possible. From geosynchronous altitude, the visible portion of the earth is a circle with a radius of about 81-1/2° latitude. Cloud cover near the edge of the circle is viewed at such an oblique angle that the entire picture will not be usable for nephanalysis. Limiting the analyzed portion of the picture to that within which the angle of view of the clouds is 45° or less will reduce the usable portion of the picture to a circle with a radius of about 40° of latitude centered at the subpoint. Even with this viewing angle, broken areas of tall clouds will appear to be overcast even though there may be substantial spaces between the cloud elements. The resulting usable cloud cover data will, therefore, consist of concentric rings with good resolution at the satellite subpoint and a gradual deterioration in detail as distance from the subpoint increases. These considerations suggest that the satellite should be positioned such that the subpoint is on a longitude just a few degrees upwind of the area of interest. This will give maximum details of the cloud cover over the area of interest and in the area from which clouds will shortly move into the area of interest.

Other data available to the meteorologist may include temperature-moisture profiles, cloud motion vectors, and some surface cloud observations from the division and battalion meteorological vans. From these several types of data, the meteorologist will prepare a nephanalysis that will provide adequate, but not excessive, details of the cloud amount and type at various altitudes (1) to aid in diagnosing current conditions over areas of various sizes and (2) to aid in predicting future weather conditions over the division and battalion areas of interest.

C. Analysis Procedure

1. Required Product

The formulation of our analysis procedure should first consider the desired end product and then work backwards to determine how the initial data could be treated to obtain the desired end product. The nature of the end product will depend on its use. The primary use will be to simplify combined information from the visible and IR data so that the meteorologist can more readily interpret the large-scale cloud pattern. It would probably not be necessary or desirable to distribute a nephanalysis to division or battalion commanders since it would not answer any of their questions about expected values of specific weather conditions. The nephanalysis then will be used only by the meteorologist as an aid in diagnosing current weather conditions and possibly as an input in short term predictions of future weather conditions. For short-term predictions of displacement of areas of similar cloud cover, the nephanalysis product might be similar to the format used in radar meteorology to reduce radarscope photographs from a network of radars to line drawings. Figure 3 is an example of the summaries made of hourly radarscope photographs. The figure shows a series of rectangles, ellipses, etc., plus points for isolated significant echoes. Detailed examination of the figure shows that the radar-detected precipitating region of the cloud cover shows some rather rapid changes from hour to hour and attempts to track the centers of areas would be difficult. Hopefully, the cloud patterns would not change as rapidly and envelopes of areas could be more readily tracked.

2. Preliminary Processing and Data Display

The manner in which the data are presented to the meteorologist is a very important factor in determining the amount of significant information he can extract from the photographs. The determination of the optimum presentation can be outlined in general terms but should be finalized

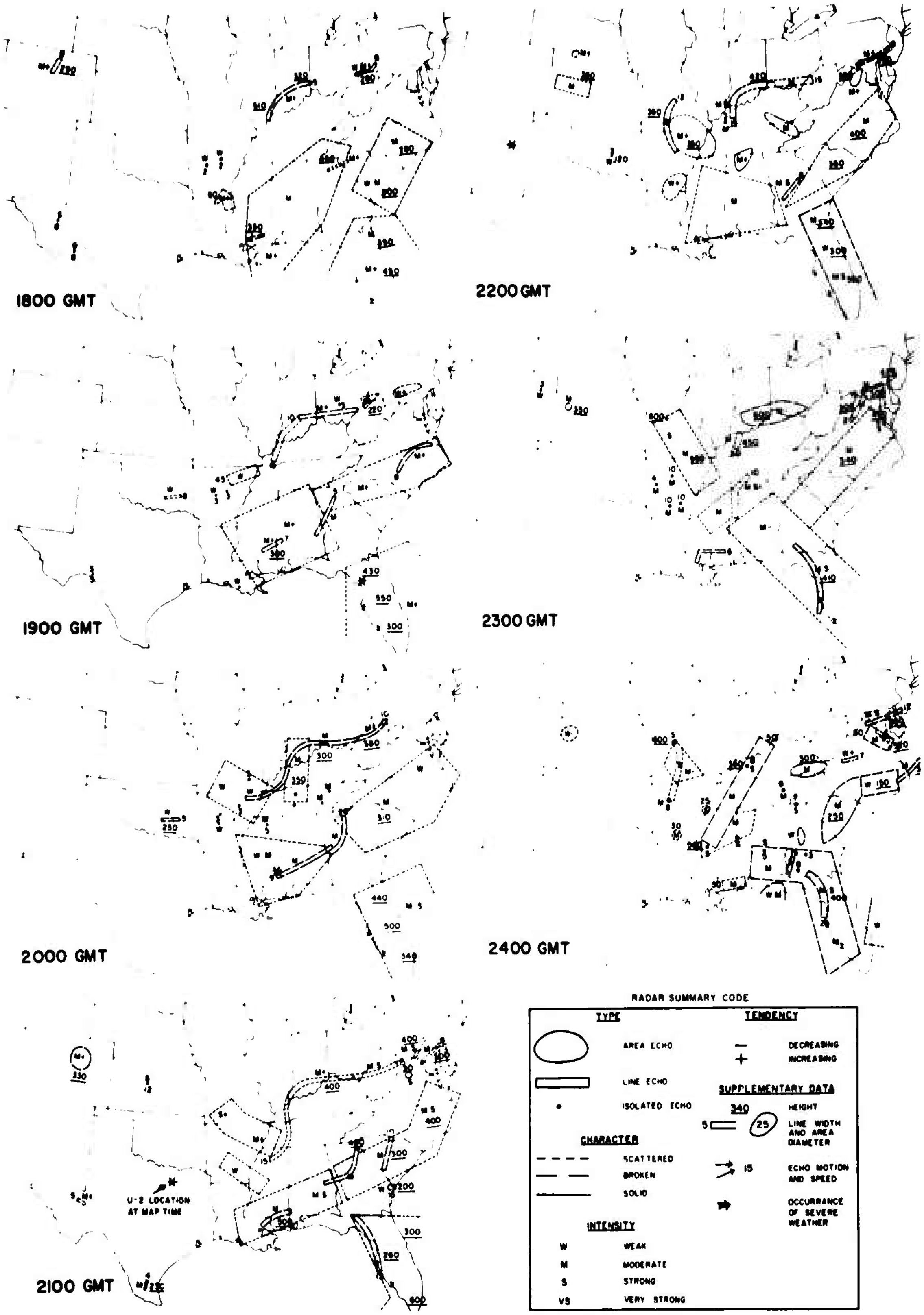

FIGURE 3 EXAMPLE OF HOURLY RADAR SUMMARY

by actual experimentation with several methods. First the photographs should have an accurate geographical grid superimposed. This grid should not obscure any significant cloud features, and to determine whether any features are obscured, it may be necessary to be able to compare a gridded and ungridded version of the same picture. In connection with gridding, the question arises as to whether a grid should be fitted to the earth as it appears from satellite altitude or whether the satellite picture should be "distorted" to fit a mercator, polar stereographic, or other map projection. There are advantages and disadvantages to fitting the picture to a specific map projection. The advantages are that it may be easier for the analyst to compare cloud cover over one area with that over a more distant area when the foreshortening away from the subpoint is removed. The disadvantage is that close to the horizon where the clouds are viewed obliquely instead of vertically even the most accurate rectification may give a false picture of the true nature of the cloud cover. Further, there is the possibility of substantial gridding errors at large distances from the subpoint, since such a small distance on the picture covers such a large distance on the earth. This, then, is one aspect of the problem that needs further study. In this study, consideration of the maximum distance toward the horizon, which is important in making a 48-hour forecast, will be one of the determining factors.

While considerable information can be obtained from a single photograph (or simultaneous pair of visible and infrared photographs), the ability to view a series of pictures in time lapse mode is necessary to extract the details required for the MIS. The initial analysis should begin with a 24-hour sequence of photographs so the diurnal variation of the cloud can be studied. The ability to see such changes as cumulus forming, in what was initially a clear area, developing into thunderstorms with anvils, and then dissipating except for some residual high or middle cloud cover from the anvils, is typical of the additional information available from time lapse viewing.

3. Required Detail

In the nephanalysis of cloud photographs it seems best to make two sets of analyses. First, over a large area (say 50° on a side) it is postulated that features covering less than 5° of latitude would not be considered unless they have considerable synoptic significance; examples would be small hurricanes or typhoons. These synoptic features would be bounded by an ellipse or other geometric configuration that best describes the shape, and would possibly be amenable to computer recognition of the center of the feature for computation of movement. The degree of homogeneity of the cloud cover within an area is subject to further analysis but an attempt would be made to maintain as much homogeneity as possible in type and amount of cloud cover and vertical extent of the cloud cover over an area. These so-called masks or envelopes would encompass such cloud features as:

- Frontal bands
- Squall lines
- Areas of thunderstorms
- Areas of nonthunderstorm cells
- Nonfrontal bands
- Vortices (both low pressure areas and vorticity centers)
- Fog
- Clear areas.

The analysis of cloud cover over a division size area would follow a similar format, but for this small area, the size of cloud features that would be considered significantly different would be much smaller. If on a 50° by 50° grid 1/10 the grid size of 5° was considered the minimum size of significant elements, on a 3° by 3° grid this 1/10 value might be retained, and features of a size of 1/3 of a degree combined to keep the analysis as uncomplicated as possible except when smaller features were considered especially significant.

4. Potential Procedure

Analysis of various types of data on SRI's ESIAC[4] (Electronic Satellite Image Analysis Console) has resulted in the development of methods by which much quantitative information on cloud cover could be generated and incorporated in nephanalysis. One of the capabilities of ESIAC is the ability of the operator to generate a "mask" of any desired size and shape. It is then possible to perform various operations on the cloud cover within the boundaries of the mask. One of the operations of interest in nephanalysis is the ability to determine the percentage of total cloud cover or the percentage of cloud cover with selected values of brightness. One can also quantitatively determine the amount of cloud cover with various temperatures from analysis of the IR photographs.

In the analysis of visible and IR photographs, the ability to combine the photographs and identify the following four categories of brightness and temperature is of importance.

(1) Bright/cold

(2) Dark/cold

(3) Bright/warm

(4) Dark/warm.

The first category would indicate optically dense clouds extending to high altitudes. The second would indicate thin cirrus clouds. The third category would indicate dense low-level cloud cover while the fourth would indicate areas in which no clouds were present. These generalizations do not take into account all the secondary effects that could result in misinterpretation of the combination of brightness and temperature.

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[4] S. M. Serebreny, W. E. Evans, and E. J. Wiegman, "Study of Time-Lapse Processing for Dynamic Hydrologic Conditions," Final Report, NASA Contract NAS5-21841, Stanford Research Institute, Menlo Park, California (September 1974).

Actual interpretation will require knowledge of surface temperature and the temperature profiles from the surface to the cloud tops. These data should be available or desired from analysis of VTPR data.

For nephanalysis, then, the meteorologist should be able to view the pictorial data in a number of readily selectable forms and combinations. First, he should be able to time-lapse a series of pictures (probably high resolution visibles) over a large area to gain an appreciation of the large scale synoptic pattern. In such viewing, differential motion should give a first clue about relative cloud altitudes--i.e., jet stream cirrus could be differentiated from slower moving lower clouds. This time lapse viewing would also aid in determining boundaries of areas of generally homogeneous cloud cover. For example, an area that initially appeared clear might subsequently show development of cumulus clouds and should therefore be included in the same category with cumulus clouds adjacent to the area.

On the last picture in the series, the meteorologist could draw tentative boundaries outlining the areas of similar cloud cover, making the areas as large as possible and the boundaries smoothed as much as possible and in the shape of triangles, ellipses, rectangles, or other simple geometric shapes.

At this point, it is difficult to state how a time-lapse sequence of IR photographs should be handled. One possible procedure would be to threshold the data and view only those clouds colder than a selected temperature. This would show time changes in the higher clouds. Thresholding to show only clouds warmer than a given temperature might be misleading because many of the lower clouds might be obscured by the colder higher clouds. In any event, viewing the IR photographs would enable the meteorologist to refine the boundaries of areas of cloud cover drawn from the visible picture or, alternatively, to draw a set of boundaries based on IR photographs alone.

The meteorologist could then superimpose the two sets of boundaries to get a first indication of the variability of cloud heights in what appeared to be homogeneous areas of cloud cover.

Following this subjective analysis of the cloud pattern, the meteorologist could proceed to objective analysis of the type mentioned above. That is, by slicing at various temperature and brightness levels and, by comparison of the slices (possibly by superposition in color), isolate the four categories indicated earlier. As mentioned previously, the slicing technique can give the percentage of cloud cover within a given area, and could be designed to give mean height and standard deviation of height over a given area.

5. Application of Techniques to Specific Cases

Satellite data for two periods have been examined. These were 11-15 June 1973 for which ATS III were available and 9-14 December 1973 for which a series of DAPP visible and infrared photographs were available. For both series, supporting meteorological data were also available.

a. 11-15 June 1973 ATS III Series

It was difficult to determine cloud types in this series of ATS photographs because of the low resolution and the scale of the photographs. A movie loop made from all available photographs in the series was useful in showing differential cloud motions. An example of the type of cloud information that could be extracted from this series of photographs has been superimposed on one of the photographs in the middle of the series (see Figure 4). Assuming that the more rapidly moving clouds were cirrus, it was possible to outline areas of cirrus. The figure shows areas that appeared to be cirrus together with areas

FIGURE 4 ATS-III NEPHANALYSIS FOR 13 JUNE 1973

that appeared to be cumulus or cumulonimbus. The bright circular area labeled stratiform may be a mixture of cirrus, altostratus, and lower clouds but the exact types could not be clearly established. In the lower right portion of the figure upper clouds could clearly be seen moving rapidly toward the northeast while the lower cumulus were moving toward the west. Thus time-lapse viewing is an essential requirement for neph-analysis when other methods of obtaining relative cloud heights are not available.

b. <u>9-14 December 1973 DAPP Series</u>

This series was chosen for analysis because of the availability of high resolution (1/3 nautical mile), visual (0.4 to 1.1 μm), and

either 1/3 or 2 nautical mile resolution infrared (8 to 13 μm) photographs from DAPP satellites. A detailed discussion of DAPP satellite data is given by Blankenship and Savage.[5] These photographs do not cover an area as large as the 50° × 50° proposed for large area analysis and also are so far apart in time that information provided by time-lapse viewing of photographs at frequent intervals cannot be simulated. They do, however, show how the combination of visible and IR pictures provide information on the distribution of clouds at various altitudes.

Figure 5a shows a 16-level IR photograph taken at 0814 GMT on 10 December 1973 while Figure 5b is a four-grey-shade IR photograph taken at the same time. The photographs show an area of stratiform clouds in the extreme upper left, an area of cellular clouds immediately southeast, a relatively bright band of clouds extending northeast-southwest across the photograph with some high cold patches in it (whitest areas in Figure 5b), and a low stratiform cloud southeast of the band. This last cloud covers the northeast-southwest band that merges with the more northerly band in the center of the photograph.

Figure 6 shows the shapes of areas that were selected for analysis on ESIAC. In this example, only very simple shapes were used and only two portions of the photograph were examined. In Figures 6a and b, a mask was placed over all the photographs except for the triangular area in the upper left corner. Controls were then set so that only the brightest 25 percent of the clouds in the area were displayed. These are shown in Figure 6a while Figure 6b shows the brightest 50 percent of the clouds. The percentages of the area of the triangle covered are 3.4 and 14.0 percent, respectively. The brightest cloud cover is in the stratiform area at the extreme upper left corner of the photograph and the

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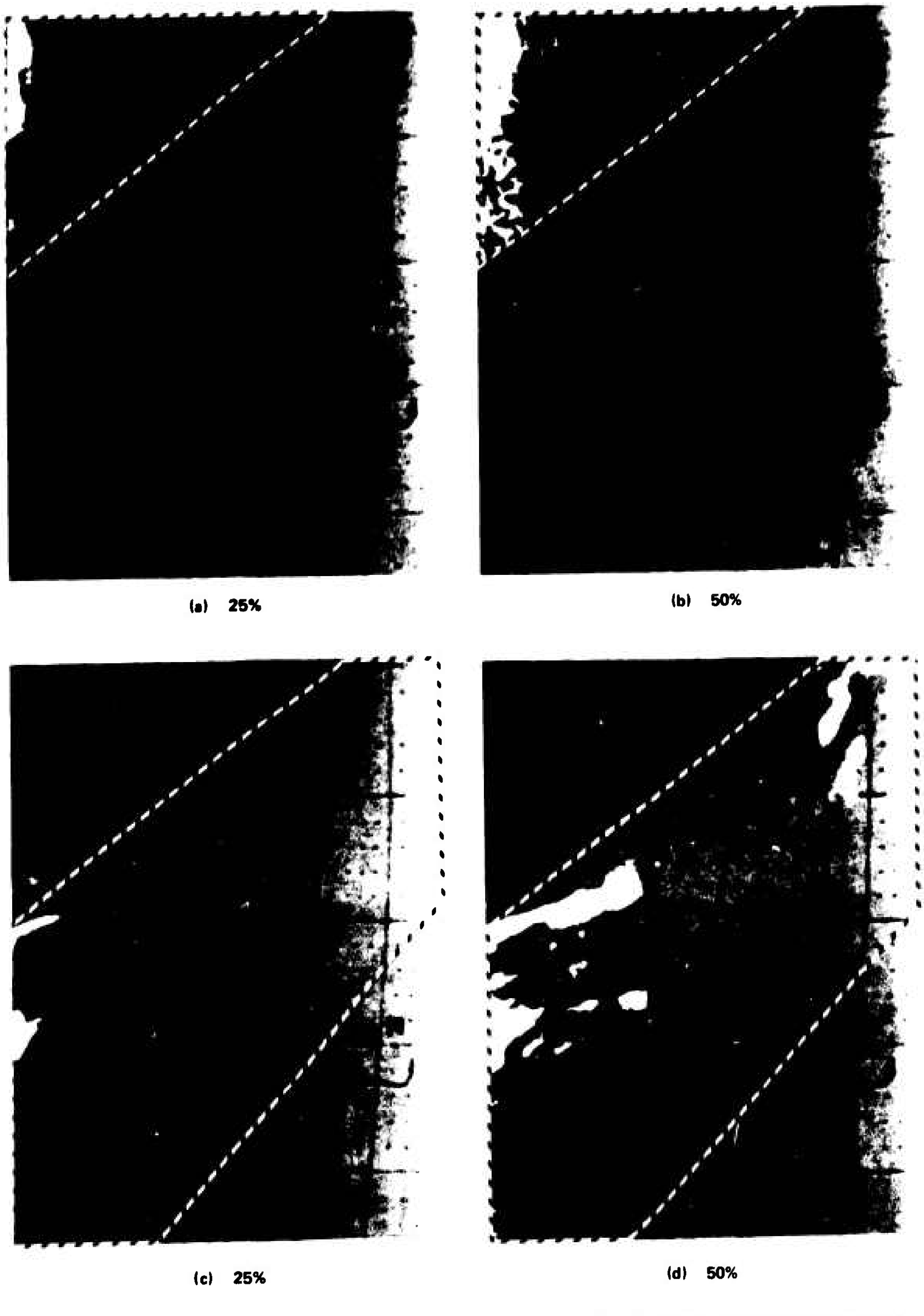
[5] J. R. Blankenship and R. A. Savage, "Electro-optical Processing of DAPP Meteorological Satellite Data," <u>Bull. Amer. Meteor. Soc</u>., Vol. 55, No. 1, pp. 9-15 (1974).

(a) SIXTEEN GREY SHADE IR

(b) FOUR GREY SHADE IR

FIGURE 5 DAPP IR PHOTOGRAPHS FOR 0814 GMT, 10 DECEMBER 1973



(a) 25%

(b) 50%

(c) 25%

(d) 50%

FIGURE 6 LOCATION OF BRIGHTEST 25% AND 50% OF CLOUDS WITHIN SELECTED AREAS OF FIGURE 5a

cellular cloud cover does not appear in the slices. In actual use, therefore, the shape of the mask would be changed to treat the stratiform clouds separately from the cellular clouds.

In Figures 6c and d the brightest 25 percent and 50 percent of the cloud cover within the outlined area has been considered. The percent of the total area covered is 1.3 and 7.9 percent, respectively. Again a larger mask leaving a smaller area to study would have been advantageous but this is only a potential procedure, not a detailed analysis.

Comparison of the brightness thresholds on Figure 6 with the four-grey-shade IR photograph in Figure 5b shows that many of the brighter areas correspond to the colder clouds. To determine more precisely the degree of correspondence, the ability to superimpose the thresholded brightness over the four-grey-scale IR photograph, as can readily be done on ESIAC, should be available.

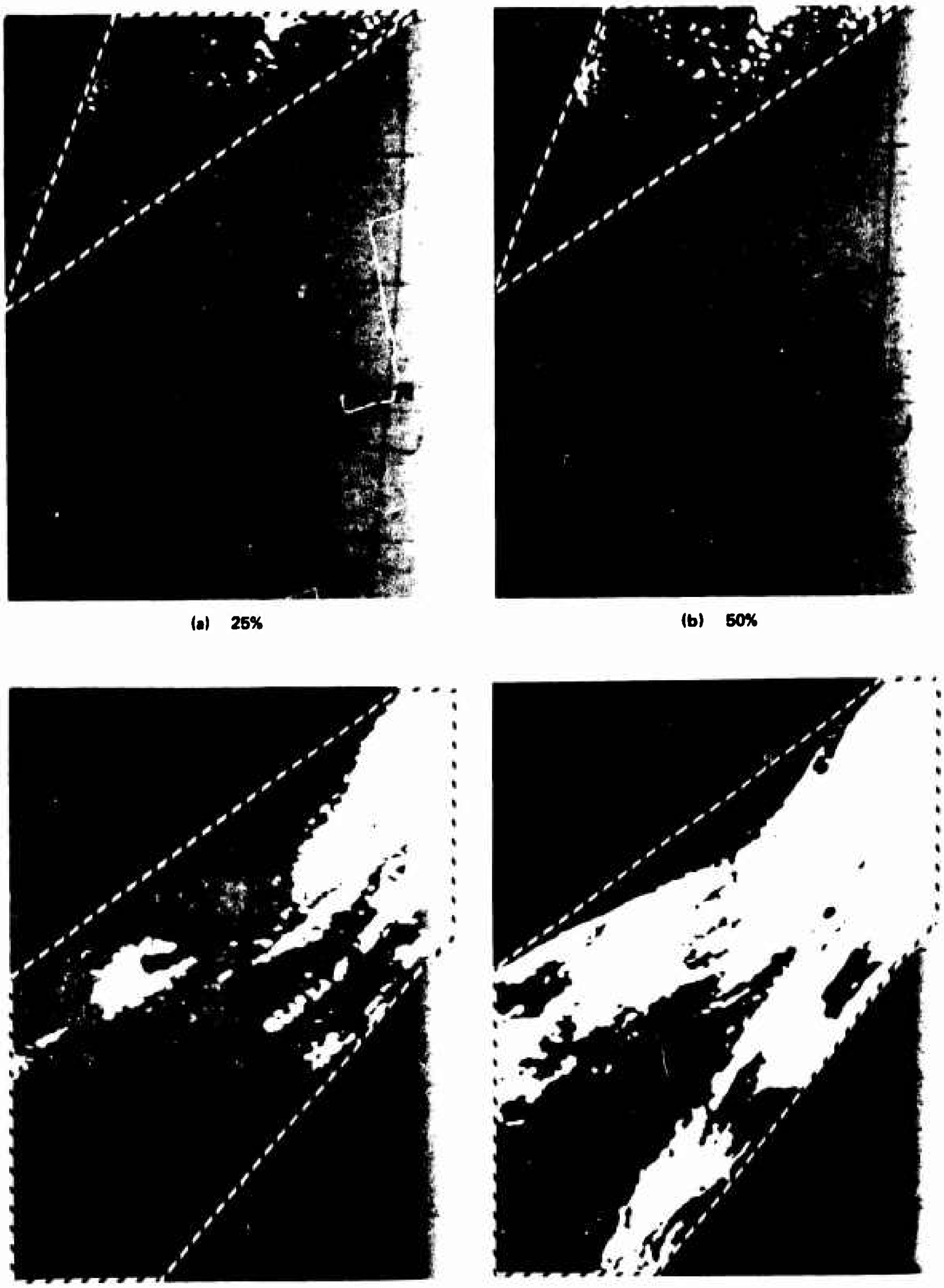
Figure 7 shows the visible and four-grey-scale IR photographs at 1240 GMT (4 hours and 26 minutes later). The same cloud features evident in Figure 5 are still present at this time but displaced slightly southeastward. Comparisons of Figures 5b and 7b show some changes in position and extent of the high level (brightest patches within the band).

On this figure the triangular mask has been adjusted so that only the cellular clouds are included within its borders. When the area is sliced to show the brightest 25 percent of the clouds, the results are as shown in Figure 8a and the brightest 50 percent is shown in Figure 8b. The areas covered are 1.4 and 3.7 percent, respectively. Within the broadband (Figures 8c and d) the 25 and 50 percent coverage by the brightest clouds is 19 and 55 percent, respectively. Comparison of Figures 8c and d with the four-grey-shade IR photograph in Figure 7b shows much bright cloud that is not cold (dense low clouds) and some cold cloud that is not bright (thin cirrus).

(a) VISIBLE

(b) FOUR GREY SHADE IR

FIGURE 7 DAPP VISIBLE AND IR PHOTOGRAPHS FOR 1240 GMT, 10 DECEMBER 1973



(a) 25%   (b) 50%

(c) 25%   (d) 50%

FIGURE 8 LOCATION OF BRIGHTEST 25% and 50% OF CLOUDS WITHIN SELECTED AREAS OF FIGURE 7a

A calibrated IR photograph preferably with more than four grey scales could be similarly treated to get the area of cloud cover at various altitudes (using VTPR data to relate temperature to height). From such treatment, the mean height of cloud tops over an area could be computed, and if desired, the standard deviation from the mean height could also be computed.

6. Discussion and Recommendations

The objective treatment of various areas of cloud cover as described in the preceding paragraphs would appear to provide the meteorologist with much useful information for diagnosis and short-term extrapolation of cloud cover. The method can provide boundaries, which can be stored and processed by computer, and also provide quantitative information on cloud amount at various altitudes. The meteorologist would be required to name the type of cloud cover if the traditional names, such as stratocumulus, altostratus, and cirrus, were desired, or he could merely use the cold-bright, warm, bright, cold-dark, warm-dark classifications which probably would be as useful as names.

It is recommended that this suggested nephanalysis procedure be tested using visible and IR data from a synchronous satellite to make analyses over both a large area and a local area such as the division area of interest. In this test, the photographs should be subdivided into more areas than those used in this example, and the additional detail provided by the time-lapse capability should be incorporated to obtain the most meaningful boundaries for various areas of cloud cover. Experimentation with several series of cloud photographs should readily show whether this method would be optimum or whether some new approach would be more suitable. The final method used will, of course, be the one that provides the meteorologist the maximum amount of information he feels he needs with a minimum of time and effort.

III TEMPERATURE INFORMATION FROM INFRARED RADIOMETERS

A. Introduction

Radiance measurements in the infrared spectral regions contain information on the thermal emission from the surface, from clouds, and from the absorbing constituents of the atmosphere. The proper interpretation of any one component is dependent on the role of all components. A direct analysis of suitably enhanced infrared imagery usually will provide useful relative information on differences in cloud heights in cloudy areas, changes in surface temperature in clear areas, or even horizontal thermal or moisture gradients from radiances at high elevations. However, the most difficult problem is that of inferring the vertical profiles of temperature and humidity in the atmosphere, especially over land surfaces. Primary emphasis in this study task has been given to the problem of atmospheric temperature retrieval, since it is this process that will be most important to the software requirements of the system.

B. Anticipated Data and Display Requirements

Radiometric hardware systems that are likely to be installed on geosynchronous satellites will require careful study and development. For initial planning considerations, it is reasonable to anticipate the deployment of a multispectral scanning radiometer system covering at least eight different spectral regions. The design might allow different fields of view for different spectral channels; the corresponding spatial resolutions could vary as much as several orders of magnitude. Measurements at the highest spatial resolution (approximately 1 km) might be desired from one visible and one infrared window channel for the deduction of detailed

surface and low cloud information. In the region of strongest CO_2 absorption, where a narrow spectral channel is required, the field of view will be large enough to encompass a spatial resolution covering more than 50 nm on a side. Such a system is logical since the best spatial resolution will be used for earth-atmosphere regions with greatest spatial variability and the poorest spatial resolution will be used for the higher atmospheric regions with the least spatial variability. The system of radiance measurements will allow meaningful retrievals of temperature profiles with techniques currently applied to systems on polar-orbiting satellites. Adequate signal-to-noise ratios are obtained by broadening the spectral resolution for measured responses from the lower atmosphere and by broadening the spatial resolution (field of view) for responses from the higher atmosphere.

At those times when atmospheric profile retrievals are not being attempted, it is assumed that updated sequences of separate imagery representing data from each channel of the scanning radiometer system will be available to the analyst. Although some information contained in the imagery from different channels will be redundant, other information will be unique to one or two channels. Those channels that produce imagery restricted to the upper troposphere and stratosphere will enable rapid recognition of horizontal thermal gradients in those regions of the atmosphere, along with associated variations in the vertical structure of the wind. At lower altitudes the horizontal and vertical distributions of cloudiness must be contended with. Since the spatial resolution inherent in the imagery for different channels will vary, it will be necessary for the analyst to have the capability to rapidly degrade the resolution in any given image to the poorest spatial resolution available in any image with which it is compared. Such a capability will assist in the proper coregistration of images pertaining to different spectral channels and will aid in both interpretive and retrieval applications. In addition, the capability to observe apparent changes in cloudiness with changes in spatial resolution will provide some information on cloud spacing and thickness.

Several other display features will be needed for proper interaction by the analyst. On any given image, an option should exist for enhancement of background contrasts in some desired portion of the total brightness range, along with a capability to adjust a threshold to some desired level. It should be possible to introduce false color to distinguish combinations of radiances observed from different channels, or to retain brightness variations in the visible while introducing superimposed color to distinguish temperature ranges in an infrared channel. The operator-analyst should have the facility to enter pertinent boundary or background information on a type of console, similar to the SRI ESIAC, and such information should be transferable to imagery from other spectral channels. Finally, with the aid of a cursor, it should be possible to recall pertinent digital information for that location and to display on an auxiliary oscilloscope a waveform that describes the latest retrieved temperature profile in the proximity of the cursor position.

C. General Utilization of Infrared Data

Radiometric data will be used in nephanalysis, cloud motion analysis, the analysis of surface temperature changes in time and space, and identification and tracking of changing weather patterns, in addition to the retrieval of horizontal and vertical profiles of temperature. Results from the nephanalysis and surface temperature analysis can be fed into the profile retrieval process; selection of retrieval sites might be governed by these analyses. During the actual temperature profile retrieval process, a direct link to prognostic output would enable specification of useful first guesses of temperature-moisture profiles for retrieval. Retrieved temperature-height data would assist in the analysis of density changes, winds and cloud motions, and could be combined with other software routines to compute radiation balance and estimates of overall energy exchange associated with the identified synoptic-scale circulation patterns.

An initial classification of cloud types can be based on the appearance and organization of cloud elements, their relative motions (in time lapse), and on differences apparent in the multispectral imagery. For example, if the presence of clouds is associated with reduced radiances in an infrared window channel but not in a strong absorption band of CO_2 or H_2O, then the cloud exists only at the lower elevations. As distinctions by type and height are made, it is also possible to provide assessments of the cloud amount. Subsequently, in conjunction with initial temperature profiles, the radiometric cloud temperature can be used to infer the top height of opaque clouds and (with the aid of empirical data) the effective height of semitransparent clouds as well as the height that should be assigned to the motion vector for the cloud. The top height of opaque clouds usually differs from the effective cloud-motion height. The radiometric response from a cloud target provides some temperature-height information independently of the formal temperature retrieval process. Some moisture-height information is obtained also because of the relationship between clouds and relative humidity.

Because of its significance to a variety of applications, considerable attention must be given to a comprehensive format to describe in a simple way the results of an initial nephanalysis (for scales equal or exceeding the smallest synoptic scales) that will be useful for a variety of applications. For example, boundaries might be sketched to define binary masks that will encompass a recognizable cloud organization or area with a reasonably homogeneous distribution of cloud elements. Each area would also be identified with a symbol that describes the classification (cloud band, vertical cloud shield, connective cloud clusters, clear, broken but unorganized cloud cover, etc.); some of the areas would be ellipsoidal with major and minor axes describing features of the overall orientation. For some cloud patterns, only the axes may be indicated. Locations of centers of the nephanalysis areas, as well as shapes and

total areas, can be tracked for changes in time-lapse sequences of images. Within any of the identified areas, analyses of digital infrared data (including summaries of means and standard deviations) would enable estimation of changes in gross heights and amounts of clouds, or changes in surface temperatures in clear areas. Multilayered clouds also could be distinguished by noting differential motions in the time-lapse sequences of images. This information is essential to a proper interpretation of digital data or for cloud motion analyses. Time-lapse sequences also aid in the identification of fog and low stratus by their diurnal variations.

D. Temperature Retrieval

1. General Considerations

Although the microwave spectral region offers good possibilities for temperature-moisture profile retrievals, present considerations have emphasized only the infrared spectral regions. However, aside from the greatly reduced cloud influence in the microwave region, retrieval techniques are similar. Furthermore, the major purpose of the present review was to establish a basis for estimation of system software requirements (incorporated in another volume of this report) relating to temperature retrievals. In contrast to previous operational retrievals, retrievals over land backgrounds, rather than ocean backgrounds, were considered exclusively. Of course, retrievals over land introduce additional uncertainties associated with time and space variations in the temperature and height of the heterogeneous lower boundary, as well as air/ground interface temperature discontinuities.

Cloudiness generally causes serious problems in temperature retrievals, but a number of other basic problems exist. A general difficulty results from the fact that measured multispectral radiances respond to thick overlapping atmospheric layers. With typical measurement noise,

the response characteristics eliminate the possibility of inferring detailed (fine-scale) structure in the vertical temperature profile.

Unique solutions of the nonlinear integral equation for upwelling radiance in terms of the temperature profile generally do not exist. Particular solutions depend on the method selected and on the initial information introduced. Some techniques, with the introduction of excessive initial (statistical) information, run the risk of merely presenting a solution that reflects the a priori information provided. Rather than depend on details of the initial information, it is preferable that the temperature retrievals based on satellite data alone should depend on:

(1) The radiance measurements.

(2) Knowledge of reliable atmospheric transmittance representations.

(3) Physical constraints of the atmosphere itself.

Within this framework, the first-guess temperature profile must be based on a standard atmospheric profile (with seasonal and latitudinal variations) to prevent the introduction of bias. Of course, after a particular solution is obtained, the resulting profile could be modified on the basis of synoptic information deduced from other satellite data. For example, position within a particular synoptic pattern might be used to reshape the derived temperature profile to include a sharp tropopause, or to include sharp temperature gradients in the lower atmosphere that typically result from orographic, cloud, diurnal, or advective influences pertaining to the local circulation. Any modifications must preserve a structure that is compatible with the measured and computed radiances and that possesses thermodynamically acceptable gradients. Such post-retrieval introduction of empirical information offers the advantage of allowing an unbiased retrieval initially.

In the discussion that follows, only the problem of the initial temperature profile retrieval is considered. Strictly speaking, the retrieval of temperature profiles cannot be separated from the retrieval of compatible humidity profiles. Not only must the two profiles be compatible, but in many spectral regions the water vapor transmittance plays a significant role in the temperature retrieval itself. Nevertheless, the present restriction to the temperature retrieval problem serves to illucidate difficulties and software requirements of retrieval.

2. Retrieval Approaches

Methods and associated problems for the retrieval of temperature profiles on the basis of radiance measurements and the integral equation for radiative transfer have been reviewed in many publications; a comprehensive bibliography on the subject has been included in a recent publication.[6] Reviews[7,8,9] pertaining to the operational experience acquired by NOAA are available, and comparisons of results obtained by various methods

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[6] Mathematics of Profile Inversion, Proceedings of a Workshop at Ames Research Center, Moffett Field, California, 12-16 July 1971, NASA Technical Memorandum, NASA TM x-62, 150. (Bibliography, Passive Atmospheric Sounding, pp. 1-77 to 1-86.)

[7] S. Fritz et al., "Temperature Sounding from Satellites," NOAA Technical Report NESS 59, National Environmental Satellite Service, Washington, D.C. (July 1972).

[8] L. M. McMillin et al., "Satellite Infrared Soundings from NOAA Spacecraft," NOAA Technical Report NESS 65, National Environmental Satellite Service, Washington, D.C. (September 1973).

[9] W. L. Smith, H. M. Woolf, and H. E. Fleming, "Retrieval of Atmospheric Temperature Profiles from Satellite Measurements for Dynamical Forecasting," J. Appl. Meteor., 11, pp. 113-122 (1972).

of solution have been presented also.[10] No attempt is made here to repeat comprehensive reviews of inversion (retrieval) techniques.

Of course, one method for inferring atmospheric temperature structure from satellite radiometric observations is by brute-force statistical regression techniques. Such an approach requires simultaneous satellite measurements and independent in situ observations of temperature profiles, presumably grouped by latitude and season. Any derived relationships would be altered each time the instrumentation was changed. Although regression techniques usually downplay extraordinary events, the approach would be most useful for large-scale analyses of data from only a few spectral channels. In this study the full regression approach will not be considered; instead, only methods that take advantage of existing knowledge of atmospheric transmittance will be considered. Furthermore, for convenience only, the significance of the nonlinear adjustment at each iterative step, as proposed by Chahine,[11,12] are not examined here. However, two different approaches to temperature retrieval based on linear adjustment algorithms are compared below.

The basis for the remote vertical sounding of the atmospheric temperature is to observe the thermal infrared emission arising from different layers in the absorbing-emitting atmosphere. The observational approach considered here is one of multispectral radiance measurements over different portions of a carbon dioxide absorption band; spectral

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[10] H. E. Fleming and W. L. Smith, "Inversion Techniques for Remote Sensing of Atmospheric Temperature Profiles, Proc. 5th Symp., Temperature, Its Measurement and Control in Science and Industry, Washington, D.C. (June 21-24, 1971).

[11] M. T. Chahine, "Determination of the Temperature Profile in an Atmosphere from Its Outgoing Radiance," J. Opt. Soc. Am., 58, pp. 1634-1637 (1968).

[12] M. T. Chahine, "Inverse Problems in Radiative Transfer: Determination of Atmospheric Parameters," J. Atmos. Sci., 27, 960-967 (1970).

regions with the strongest absorption provide information on temperature at the highest levels in the atmosphere. A spectral interval in an infrared window region is employed to sense contributions from the lower boundary. To retrieve the thermal structure through the entire atmosphere the mass distributions of the principal absorbers must be known along with the boundary conditions.

Even for the case of a cloud-free atmosphere a number of simplifying assumptions are made to enable a tractable retrieval. Each measured radiance is determined by the response characteristics of the instrument to the true radiance. Radiation within the instrument's field of view is construed to arise from a single direction. At any viewed locality the atmosphere is treated as plane-parallel (with horizontal homogeneity) in local thermodynamic equilibrium over a blackbody lower boundary. Also, in the absence of clouds, scattering of radiation is neglected. The atmospheric transmittance through any slant path x (a single-valued function of pressure) must be known for the retrieval process to be considered here. Radiances for a given initial thermal structure are computed in each spectral interval with transmittances that are averaged with respect to the spectral response function, f, of the appropriate instrument filter. If ν_i is the wave number centroid of the filter transmittance for the i^{th} channel, then the following definitions are used:

$$\tau(\nu_i, x) = \int_0^\infty \tau(\nu, x) f_i(\nu) d\nu \Big/ \int_0^\infty f_i(\nu) d\nu$$

$$\frac{d\tau(\nu_i, x)}{dx} = \int_0^\infty \frac{d\tau(\nu, x)}{dx} f_i(\nu) d\nu \Big/ \int_0^\infty f_i(\nu) d\nu$$

If there are K absorbers (e.g., water vapor and ozone in addition to carbon dioxide) in the spectral interval, then it is assumed that the joint transmittance can be defined by

$$\tau(\nu_i, x) = \prod_{k=1}^{K} \tau_k(\nu_i, x) \quad .$$

The radiance from a particular direction can now be described by

$$R(\nu_i) = B[\nu_i, T(x_s)]\tau(\nu_i, x_s) - \int_1^{\tau(\nu_i, x_s)} B[\nu_i, T(x)]d\tau(\nu_i, x) \qquad (1)$$

where the Planck function

$$B[\nu, T(x)] = C_1\nu^3 / \left\{\exp[C_2\nu/T(x)] - 1\right\} . \qquad (2)$$

In Eq. (2), $T(x)$ is the temperature at vertical position x and C_1 and C_2 are known constants. For convenience, x's are usually spaced in equal increments of pressure (p) raised to the 2/7 power.

The first term on the right side of Eq. (1) represents the radiance contribution from the lower boundary (indicated with the subscript s). A temperature discontinuity may exist between the atmosphere and the boundary surface itself. For retrieval considerations, it is usually assumed that the surface temperature $T(x_s)$ for cloudless conditions can be obtained from separate (independent) measurements, and the specified boundary surface temperature usually is held fixed during the atmospheric temperature profile retrieval process. Numerical assessments of radiance based on Eq. (1) depend critically on accurate treatments of the transmittances through the vertically-inhomogeneous cloud-free atmosphere. Computations usually are based on approximate formulations and the inherent temperature dependence of the transmittance is commonly computed only with respect to the first-guess temperature profile.

The object of the retrieval is to infer $T(x)$ such that radiances computed by Eq. (1) agree with measurements in a relatively small number of finite spectral regions (channels). Spectral channels typically employed

in the remote sensing of the atmosphere accept radiances due to emissions from thick, overlapping layers within the atmosphere. As mentioned above, these response characteristics and the presence of noise create difficulties in the temperature retrieval process, regardless of method of approach. On the other hand, the spectral intervals are narrow enough to assume that the Planck function and transmittance are essentially uncorrelated with respect to wave number over the interval. Thus, it is possible to assign a single appropriately averaged wave number to each channel for the computation of the Planck function [see Eq. (2)], and to utilize transmittances representative of the entire spectral interval for each channel.

Eq. (1) can be modified into a difference (or iterative) form by subtracting the expression involving the initial or first-guess temperature $\hat{T}$ from the expression containing the desired or improved estimate of temperature T. Let $R_M(\nu_i)$ represent the measured radiance in the i^{th} spectral channel and $R_C(\nu_i)$ represent the computed radiance for the first-guess temperature $\hat{T}$. Then the integral equation of radiative transfer becomes

$$r_i = -\int_{x_n}^{x_s} \left\{ B_i[T(x)] - B_i[\hat{T}(x)] \right\} \frac{d\tau_i(x)}{dx}\, dx \tag{3}$$

where the vector

$$\begin{aligned} r_i &= R_M(\nu_i) - R_C(\nu_i) \\ &= R_M(\nu_i) - B_i[\hat{T}(x_s)]\tau_i(x_s) + \int_{x_n}^{x_s} B_i[\hat{T}(x)] \frac{d\tau_i(x)}{dx}\, dx \end{aligned} \tag{4}$$

Boundary terms, for the assumed constant $T(x_s)$, have canceled on the right side of Eq. (3). Although not strictly valid, the $d\tau_i(x)$ term in Eq. (3) has been treated as invariant with temperature over the range $T(x) - \hat{T}(x)$. This simplification apparently is not critical to the final results.

To reshape Eq. (3) into the form of a linear Fredholm equation of the first kind, a centralization of the Planck functions to a fixed reference wave number, ν_o, is introduced to enable some separation of variables with respect to the simultaneous dependence of B on temperature and wave number under the integral. Specifically, the vector b_j is defined in terms of the unknown T(x) through

$$b_j \doteq b(x) = B_o[T(x)] - B_o[\hat{T}(x)] \tag{5}$$

at the wave number ν_o. Now Eq. (3) can be put in the form

$$r_i = \int_{x_n}^{x_s} b(x)A(x)dx \tag{6}$$

where the matrix elements of A are

$$a_{ij} = -\left[\frac{dB_i[\hat{T}(x_j)]/dT}{dB_o[\hat{T}(x_j)]/dT}\right]\frac{d\tau_i(x_j)}{dx} \qquad \text{for } T(x_j) = \hat{T}(x_j)$$

$$= -\left[\frac{B_i[T(x_j)] - B_i[T(x_j)]}{B_o[T(x_j)] - B_o[\hat{T}(x_j)]}\right]\frac{d\tau_i(x_j)}{dx} \qquad \text{for } T(x_j) \neq \hat{T}(x_j)$$

with i going from 1 through M, the number of spectral channels, and j going from 1 through N, the number of pressure levels included in the computational model.*

If quadrature weights for the numerical integration are combined with the kernel function and an error vector $\epsilon(i)$ is added to represent the errors of measurement, Eq. (6) can be rewritten in matrix-vector form

$$\underset{\sim}{r} = A\underset{\sim}{b} + \underset{\sim}{\epsilon} \tag{7}$$

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*In recent practice, both measured and computed radiances also are scaled to the reference wave number, with a resultant simple form for the kernel function A.

The basic problem of retrieval is to determine the $N \times N$ dimensional coefficient matrix C for relating the N dimensional vector b to the M dimensional vector r, in a least squares sense,

$$b = Cr \ . \tag{8}$$

Fleming and Smith[10] have shown that if the errors are assumed to be independent of b and to belong to a multivariate distribution with zero mean, then

$$C = S_b A^T [A S_b A^T + S_\epsilon]^{-1} \tag{9}$$

where the superscript T indicates matrix transpose, the -1 power indicates a matrix inversion, and S_b and S_ϵ are covariance matrices of b and ϵ. In practice, further simplifications are introduced by assuming that the different elements of b are uncorrelated and the variance S_{ii}^2 is considered constant so that $S_b = \sigma_b^2 I_N$ where I_N is the $N \times N$ identity matrix. Similarly, the elements of ϵ are also considered uncorrelated and S_ϵ is reduced to an M dimensional diagonal matrix. With these simplifications computational time is reduced and information on the covariance matrices is no longer required.

Once T(x) is recovered from the first solution for b(x),

$$T(x) = B_o^{-1} \left\{ B_o[\hat{T}(x)] + b(x) \right\} , \tag{10}$$

the process of iteration can be used to improve the results by using T(x) in place of $\hat{T}(x)$ for the next step. The function b(x) rapidly approaches zero, uniformly in x, in the iterative process.

As outlined, this approach forms the basis of the operational procedure adopted by NOAA; complete scaling to the reference wave number and the simplifications indicated for Eq. (9) are incorporated in the NOAA

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[10] H. E. Fleming and W. L. Smith, op. cit.

routine. Typically, forecast temperature profiles are used for the first guess and sea-surface temperatures are introduced by a separate routine that uses higher resolution data from a scanning radiometer. The surface temperature is held fixed during the retrieval. In the absence of other information, the humidity profile (for computing transmittances) is generated by a regression technique that relates to the first-guess temperature field. Temperature corrections on the transmittances are applied only on the basis of the first-guess field for speed and simplicity. A separate routine is applied in partly cloudy regions to generate equivalent clear column radiances from observed radiances; retrievals require this adjustment of cloud-contaminated measurements. Hereafter, the NOAA procedure will be referred to as the Minimum Information method; this label refers to the minimal statistical information required as input.

A somewhat different alternative approach is considered to enable comparison of different particular solutions that arise from related techniques. This approach also relates the solution adjustment to the first guess as a linear function of the difference between measured and computed radiances. However, the adjustment algorithm differs and is not explicitly linked to the statistics of radiance variations associated with thermal structure or measurement noise. Instead, the algorithm is employed directly without the formalism associated with solution of the Fredholm equation. Hereafter, it will be referred to as the Linear Direct method. A further distinction from the Minimum Information method is introduced by a deliberate avoidance of scaling to a central reference wave number.

The Linear Direct method is a modified version of the Smith 1970 technique.[13] The modification* was motivated by the desire to increase

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[13] W. L. Smith, "Iterative Solution of the Radiative Transfer Equation for the Temperature and Absorbing Gas Profile of an Atmosphere," Appl. Opt., 9, pp. 1933-1999 (1970).

*Due to Dr. Andrew Korsak of SRI.

the convergence rate and decrease the computational time. The independently specified surface temperature (T_s) is held constant during the retrieval, but the air temperature just above the surface is allowed to vary at each iteration step from

$$B_i[T(x)] = B_i[\hat{T}(x)] + r_i \ , \tag{11}$$

Let the Planck functions be expanded linearly about the current temperature values $\hat{T}(x)$:

$$B_i[T(x)] \doteq B_i[\hat{T}(x)] + [T(x) - \hat{T}(x)] \frac{dB_i[\hat{T}(x)]}{dT} \ .$$

Then if a general change

$$B_i[T(x)] = B_i[\hat{T}(x)] + \delta_i$$

in Planck function is made at the i^{th} frequency, the linearized effect upon the temperature profile, according to Smith's procedure, would be as follows:

Let
$$T_i(x) = B_i^{-1}\left\{B_i[T(x)]\right\} = B_i^{-1}\left\{B_i[\hat{T}(x)] + \delta_i\right\}$$

$$\doteq \hat{T}(x) - \frac{\delta_i}{dB_i/dT} \ .$$

Hence, Smith's weighted combination of T_i's is linearized to

$$T(x) = \frac{\sum_{i=1}^{M} (d\tau_i/dx) T_i(x)}{\sum_{m=1}^{M} (d\tau_m/dx)}$$

$$\doteq T(x) - \sum_{i=1}^{M} \frac{\delta_i (d\tau_i/dx)}{(dB_i/dT) \sum_{i=1}^{M} (d\tau_m/dx)}$$

Consequently, the linearized effect upon newly calculated radiances (R_c') is given by

$$R_c'(\nu_i) = B_i[\hat{T}(x_s)]\tau(x_s) - \int_{x_N}^{x_s} B_i[T'(x)]d\tau_i(x)$$

$$\doteq R_c(\nu_i) - \int_{x_N}^{x_s} \sum_{m=1}^{M} \epsilon_m \frac{(d\tau_m/dx)(dB_i/dT)}{(dB_m/dT)\sum\limits_{k=1}^{M}(d\tau_k/dx)} \frac{d\tau_i}{dx}\, dx \ ,$$

or

$$R_c'(\nu_i) = R_c(\nu_i) - \sum_{m=1}^{M} d_{im}\epsilon_m$$

where, upon neglecting dependence of ϵ on height,

$$d_{im} = \int_{x_s}^{x_N} \left\{ \frac{[d\tau_m(x)/dx]\{dB_i[\hat{T}(x)]/dT\}}{\{dB_m[\hat{T}(x)]/dT\}\sum\limits_{k=1}^{M}[d\tau_k(x)/dx]} \frac{d\tau_i}{dx} \right\} dx \ , \qquad (12)$$

x_s represents the surface level, and x_N corresponds to the uppermost pressure level. Thus, to arrive at a first order cancellation of the error in calculated radiances in one step, one should perform the following step in place of Smith's step:

$$B_i[T(x)] = B_i[\hat{T}(x)] + \sum_{m=1}^{M} e_{im} r_m \ , \qquad (13)$$

where $E = [e_{im}]$ is the inverse of $D = [d_{im}]$.

The i values of B at each pressure level in the atmosphere from Eq. (13) are inverted [see Eq. (2)] to obtain i candidate temperatures:

$$T_i(x) = c_2\nu_i/\log_e\left\{\left[c_1\nu_i^3/B_i[T(x)]\right] + 1\right\} \ . \qquad (14)$$

Finally, the true temperature at each level x is determined as a weighted average of the i independent estimates

$$T(x) = \sum_i T_i(x)\ d\tau_i(x) / \sum_i d\tau_i(x) \quad . \tag{15}$$

For the temperature to be determined at every level, it is clear from approximation (15) that at least one of the $d\tau$'s must be non-zero. After the new temperature profile $T(x)$ is defined, the new estimates are relabeled $\hat{T}(x)$ for the next iteration. Accordingly, a new set of $B_i[\hat{T}(x)]$ are computed as in Eq. (4). Subsequently, the process described by Eqs. (12) through (15) is repeated until satisfactory convergence is obtained as evidenced by a vanishing change in $B_i[T(x)]$ from step to step.

During actual applications, it was found that the matrix E would overemphasize some of the r_i's during particular retrievals. Therefore, to avoid the occurrence of unrealistic negative values for $B_i[T(x)]$ at any level, it was necessary to "pull back" the adjustment vector from the steepest extreme toward the Smith algorithm. Convergence rates were reduced significantly when the pull back was necessary.

In summary, both approaches require an initial temperature profile from which corresponding Planck functions are computed as are departures of radiances from measurements for each spectral channel. In the Minimum Information method, Planck function and radiance computations, as well as radiance measurements, are scaled to a single reference wave number. The adjustment algorithm (which includes a matrix inversion) operates on the radiance departure vector with an $N \times M$ matrix to obtain a solution in a least squares sense. The resultant revised Planck function profile is used to define the revised temperature profile, which may be used as the next initial guess for iteration. In the adopted Linear Direct method, Planck functions and radiances are not scaled to a reference wave number. The adjustment algorithm (which also includes a matrix inversion) operates

on the radiance departure vector with an M × M matrix to provide a revised Planck function in each channel at all levels. A single revised temperature profile is computed as a weighted average of the temperatures determined from the Planck functions for each channel. This revised profile is used as the initial profile for the next iteration.

3. Simulation

Simulation represents a powerful tool for the controlled comparison of retrieval techniques as long as inherent limitations are recognized. In a simulation, it is possible to specify exactly the desired, or true, profile and to simulate both the transmittance and the measurements. The danger in the simulation arises from the perfect correspondence built into the transmittance and measurement representations. Such compatibility is not experienced in the real world.

The simulation of the transmittances eliminated the complications of temperature dependence and the overlapping absorption by nonuniformly mixed gases in the computations. As an additional simplification the simulated transmittance function was defined in terms of the data-level index (100 levels) employed in the NOAA retrieval procedure:

$$\tau_i(k) = \frac{0.5 - \pi^{-1} \arctan[(i - 16k)/15]}{0.5 - \pi^{-1} \arctan[(1 - 16k)/15]} . \tag{16}$$

Channel 1 (i = 1) responds to the upper atmosphere and Channel 6 responds to the lower atmosphere as well as the boundary surface.

The derivatives of the transmittance functions with respect to the height index describe the transmittance weighting functions illustrated in Figure 9 for each of the adopted six spectral intervals. These weighting functions are similar (but slightly superior) to the actual weighting

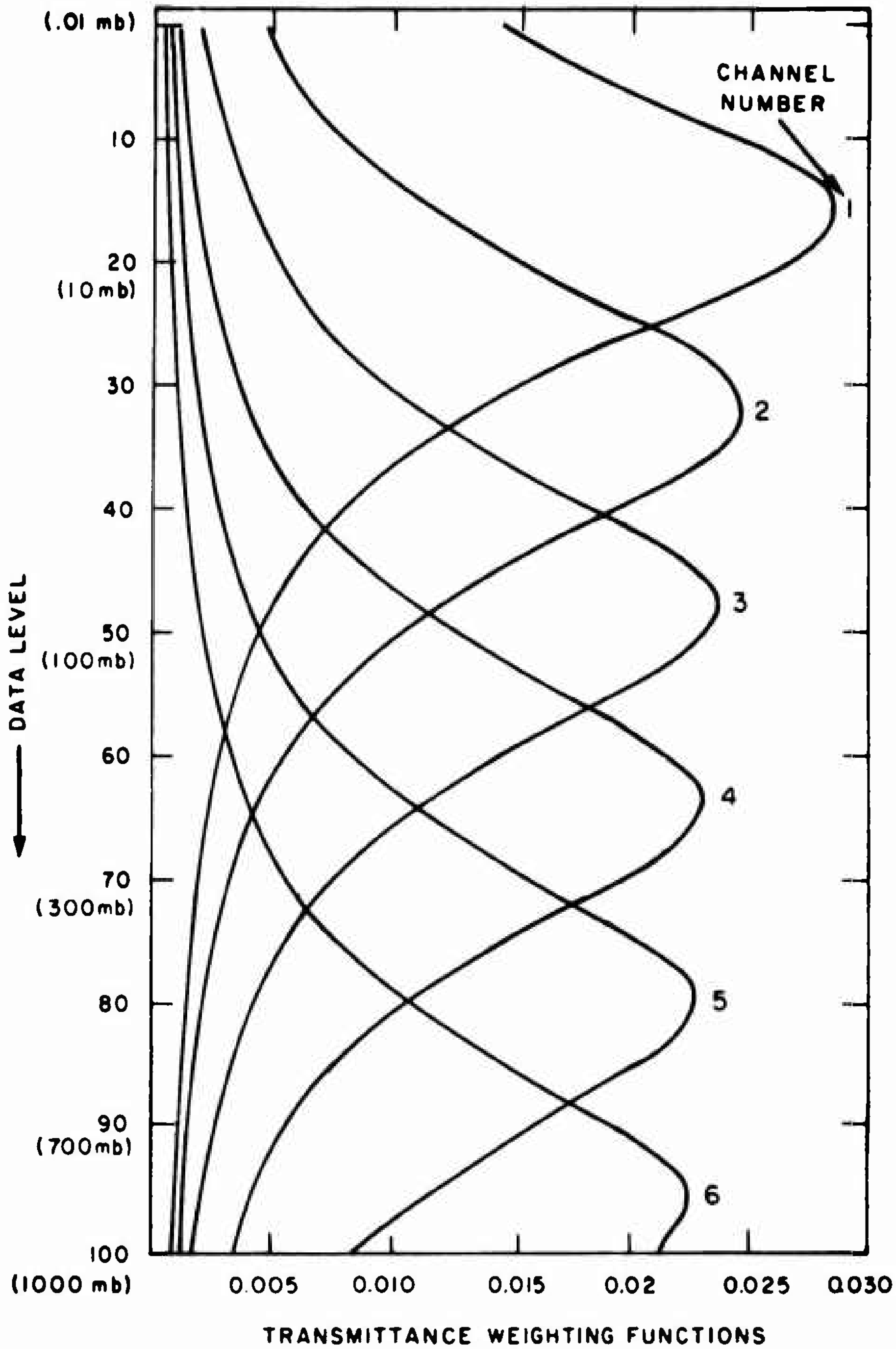

FIGURE 9 VERTICAL DERIVATIVES (WEIGHTING FUNCTIONS) OF SIMULATED TRANSMITTANCES DEPICTING RELATIVE ATMOSPHERIC CONTRIBUTIONS TO RADIANCE MEASUREMENTS IN SIX SPECTRAL CHANNELS

functions for the VTPR sounder. Each curve describes the relative weight associated with different depths in the atmosphere for contributions to the radiance observed in the particular channel from above the atmosphere.

For all simulations a "true" temperature profile was defined to show a linear decrease of temperature from 250 K at level 1 (top of model, pressure = .01 mb) to 201 K at level 50 (pressure approximately 100 mb), followed by a linear increase in temperature to 300 K at level 100 (pressure = 1000 mb), the lower boundary. The boundary temperature itself was fixed at 300 K, i.e., no temperature discontinuity was assumed at the lower boundary. This true temperature profile (shown later as the dashed line in Figures 11 and 12) also can be described by

$$T_k \begin{cases} = 251 - k, \text{ for } k = 1,2, \ldots, 50 \\ = 100 + 2k, \text{ for } k = 51,52, \ldots, 100 \, . \end{cases} \tag{17}$$

All radiance "measurements" were generated (simulated) by computation at the six selected channel wave numbers: 667.2, 677.6, 695.2, 708.0, 725.0, 747.7 cm^{-1}. Computations were based on the adopted true temperature profile and the simulated transmittance functions for the six channels.

The first exercise was conducted to verify that, under ideal conditions, the Korsak algorithm used in the Linear Direct approach did result in a faster convergence rate than the Smith algorithm of 1970. For this purpose, a poor initial first-guess temperature profile was introduced for application to both algorithms. The first-guess profile was defined as linear in k, increasing from 230.5 K at k = 1 to 280 K at k = 100:

$$\hat{T}_k = 230 + 0.5 \, k \, .$$

Results of the applications are illustrated in Figure 10; a dramatic improvement in convergence rate is indicated. After four iteration steps

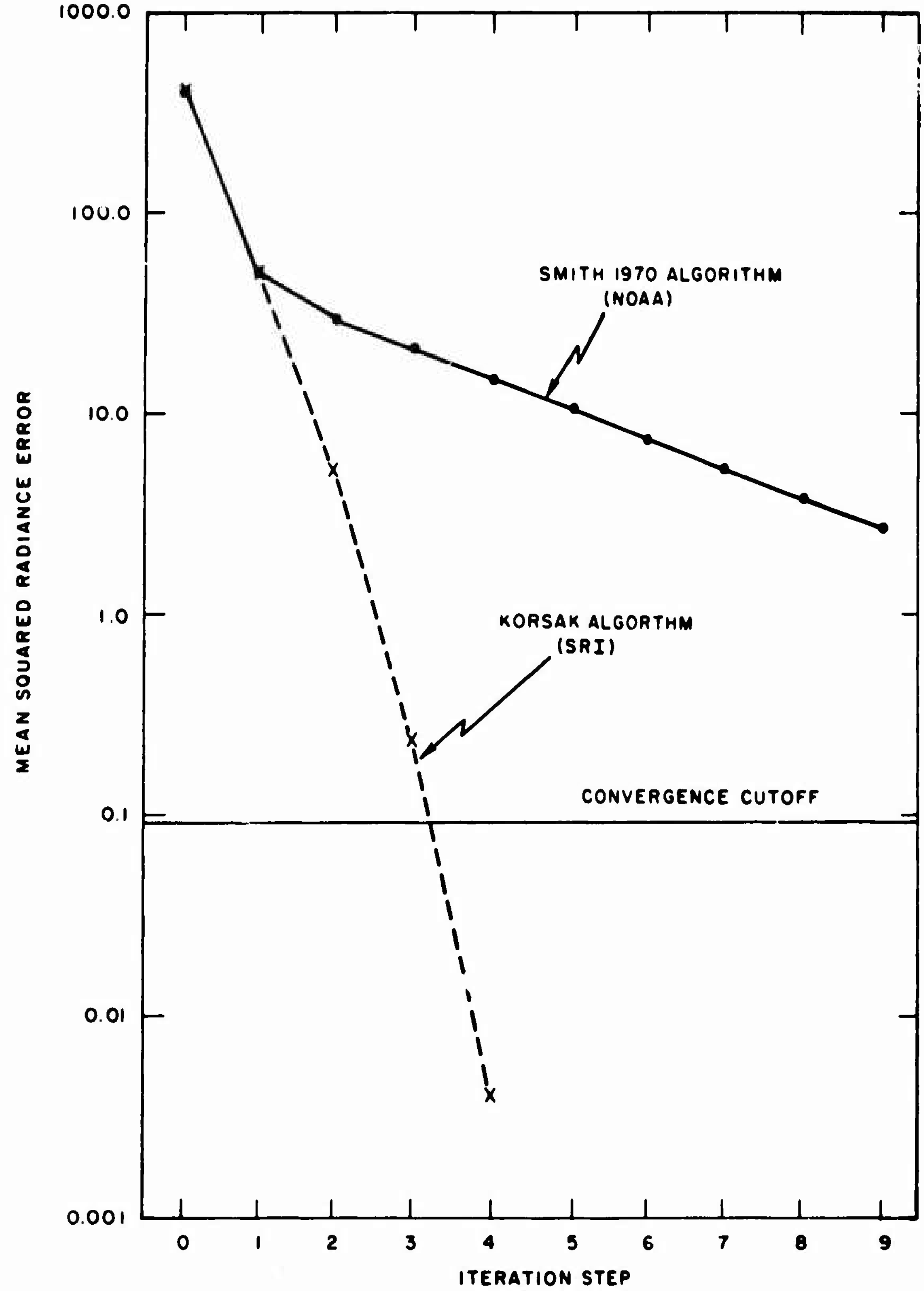

FIGURE 10 COMPARISON OF CONVERGENCE BEHAVIOR OF SMITH 1970 ALGORITHM AND KORSAK ALGORITHM FOR SIMULATED LINEAR DIRECT RETRIEVAL (CURVES REPRESENT OPTIMAL DIFFERENCES IN CONVERGENCE RATES)

the Korsak algorithm leads to a mean squared radiance departure for the "measured" results that is well beyond the established convergence criterion. However, after nine iterations the 1970 Smith algorithm is still only approaching the convergence cutoff in a gradual fashion. Not illustrated in Figure 10 is the fact that the Minimum Information approach, when used in iterative fashion, converges even more rapidly than the Linear Direct approach.

With the simulated transmittance functions defined by Eq. (16) and the artificial sounding described by (17), results of applications of both retrieval methods are shown in Figures 11 and 12. Illustrated retrievals for two initial conditions result from two iteration steps with the Minimum Information method shown on the right side, and four iteration steps with the Linear Direct method shown on the left side. On each figure, the first-guess temperature profile is depicted by short dashes, the true temperature profile by long dashes, and the retrieved temperature profile by a solid curve. Inasmuch as the boundary temperature was held fixed while the temperature at the lowest atmospheric level was allowed to shift, a temperature discontinuity is permitted at the interface. Table 1 lists the pressures associated with some of the 100 data levels used operationally by NOAA.

In the applications illustrated in Figure 11 the first-guess profile is taken as isothermal, at $\hat{T} = 250^\circ K$; noise has been added to the six simulated measurements. In Figure 12, the first-guess temperature profile consists of three linear segments:

$$
\begin{aligned}
T_k &= 240 - \frac{20(k-1)}{23} && \text{for } k = 1,2, \ldots, 24 \\
&= 220 && \text{for } k = 25,26, \ldots, 63 \\
&= 220 + \frac{17(k-64)}{9} && \text{for } k = 64,65, \ldots, 100 .
\end{aligned}
$$

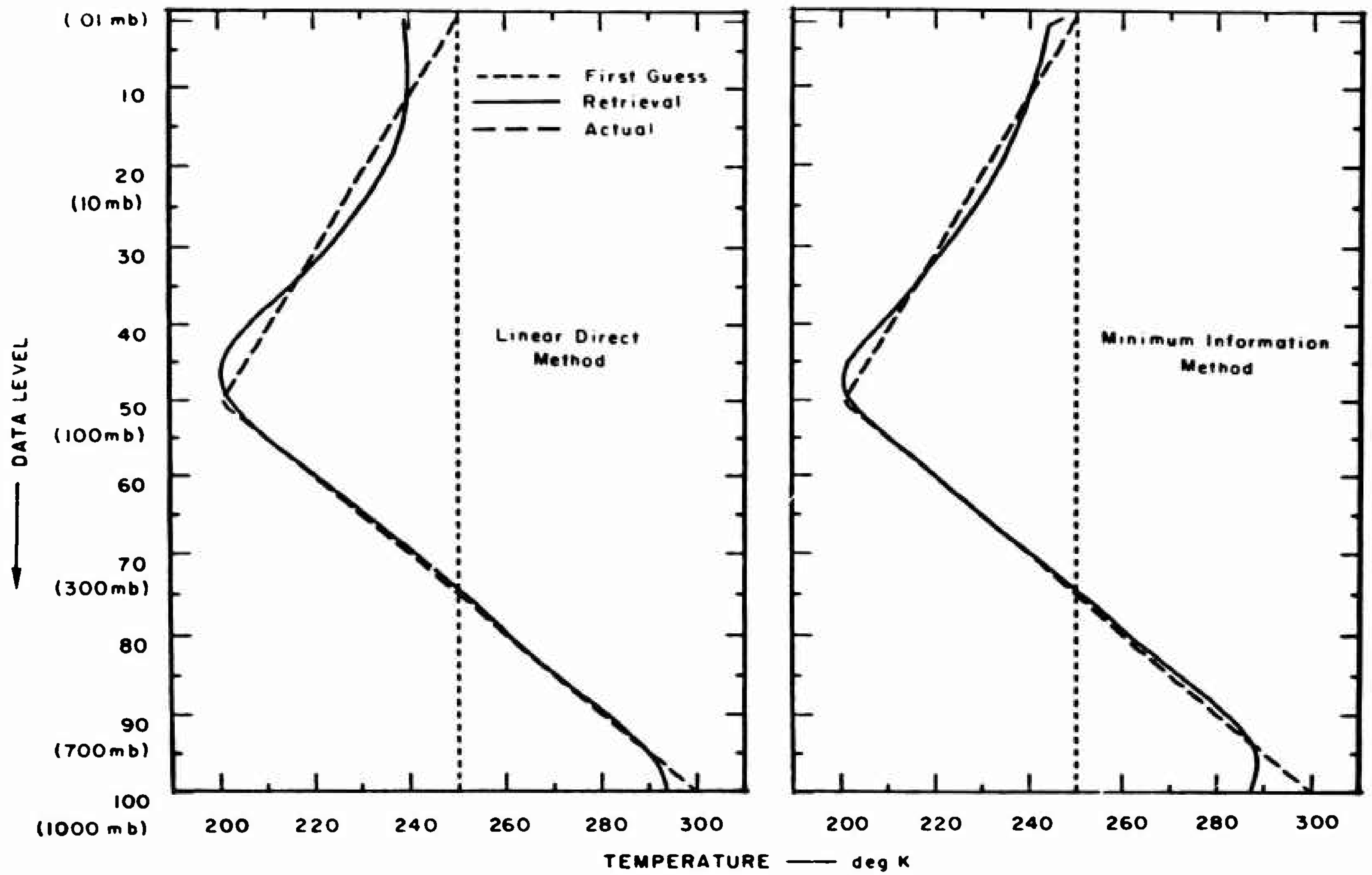

FIGURE 11 COMPARISON OF MINIMUM INFORMATION AND LINEAR DIRECT RETRIEVAL METHODS USING ISOTHERMAL FIRST-GUESS TEMPERATURE PROFILE (SIMULATED MEASUREMENTS, WITH NOISE ADDED)

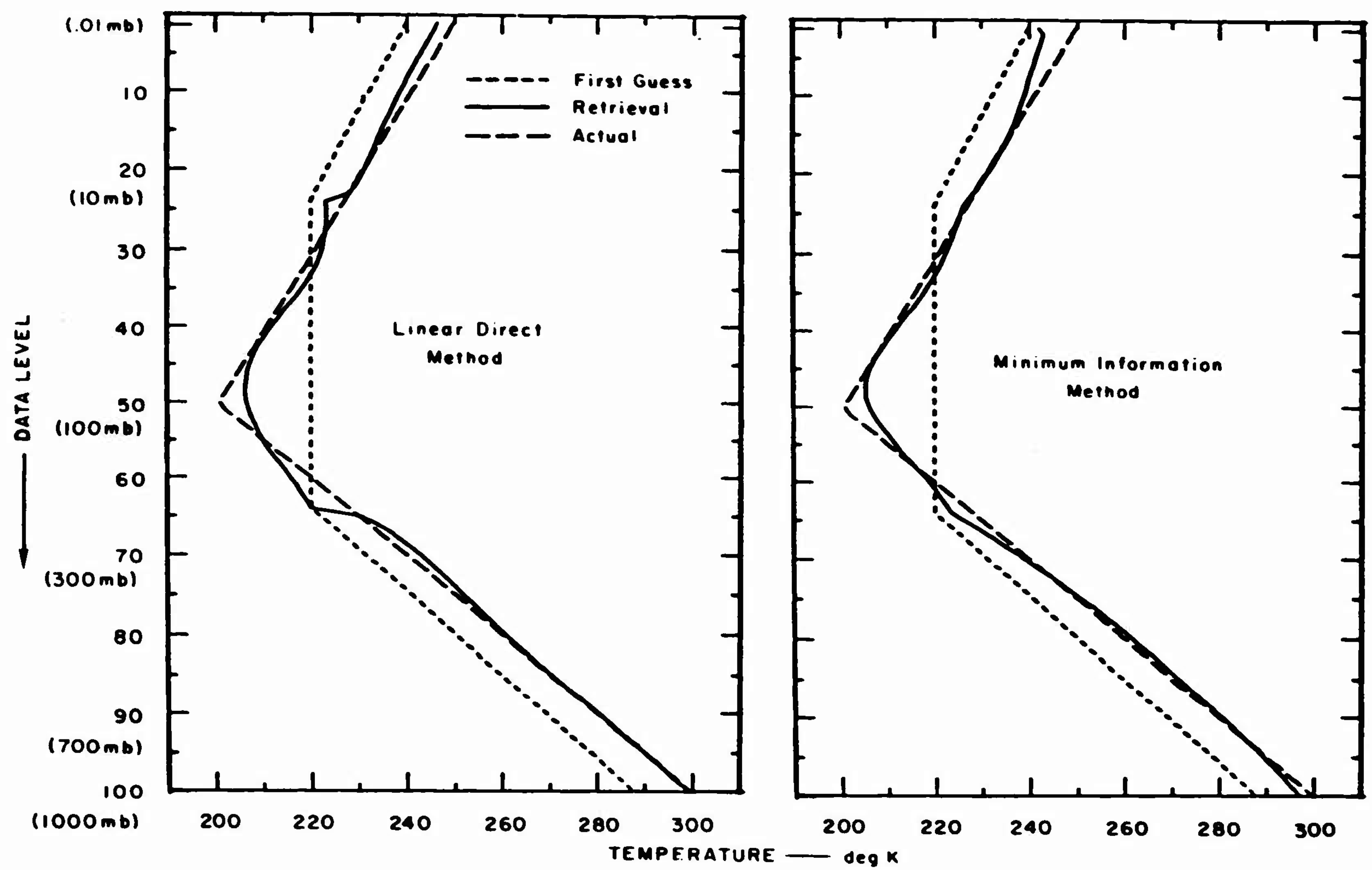

FIGURE 12 COMPARISON OF MINIMUM INFORMATION AND LINEAR DIRECT RETRIEVAL METHODS USING THREE-SEGMENT FIRST-GUESS TEMPERATURE PROFILE (SIMULATED MEASUREMENTS, WITH NOISE ADDED)

Table 1

SELECTED DATA LEVELS AND CORRESPONDING PRESSURES USED IN VTPR RETRIEVALS

Level	Pressure (mb)	Level	Pressure (mb)
1	0.01		
5	0.12	55	133.4
10	0.69	60	178.3
15	2.17	65	233.1
20	5.16	70	299.0
25	10.32	75	377.2
30	18.39	80	469.1
35	30.21	85	575.9
40	46.64	90	699.0
45	68.64	95	839.9
50	97.21	100	1000.0

The colder isothermal segment of the first-guess profile joins the other two segments in sharp corners.

Measurements are identical for both methods in each application. The addition of noise had only a minor influence on the results illustrated, but slightly more degradation was introduced in the upper portion of the profile retrieved by the Linear Direct method. In general, the Minimum Information method leads to better retrievals in the upper portion of the model atmosphere while the Linear Direct method yields slightly superior retrievals in the lower portion.

It is apparent from a comparison of Figure 12 with Figure 11 that the first-guess profile does influence the retrieval. However, the areas of the profile that appear to be affected most are the boundaries and the regions with the first order discontinuities in the first-guess profile. In particular, while the Minimum Information method tends to

adhere more closely to first-guess temperatures at the top and bottom of the modeled atmosphere, the Linear Direct method adheres much more closely to the first-guess temperatures at the points with first order discontinuities. In fact, the latter adherence is so strong that the retrieved profile shows unrealistic minima at the first order discontinuities, with unrealistic temperature gradients in the immediate vicinity of the discontinuities. This result indicates that it is desirable to avoid first order discontinuities in the first-guess temperature profile. A similar conclusion was reached from simulations based on retrieval with a nonlinear adjustment algorithm.[14] On the other hand, post retrieval smoothing of the sounding to remove unrealistic gradients would yield an improved final temperature profile also.

E. Application of NOAA-2 VTPR Data Over Land

1. Software and Data

A realistic assessment of retrieval approaches and their software requirements can be accomplished by applications of real data. The applications of interest occur over land areas where operational retrievals by NOAA were not available. Furthermore, surface temperatures, first-guess temperature profiles, and equivalent clear-column radiances in partly cloudy areas also were not available. Thus, the limited scope of this study necessitated a number of simplifications for the application of raw radiances from the VTPR on the NOAA-2 satellite.

Printouts of principal segments of NOAA computer programs used in their Minimum Information retrieval method were obtained* along with

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[14] J. S. Hogan and K. Grossman, "Test of a Procedure for Inserting Satellite Radiance Measurements into a Numerical Circulation Model," J. Atmos. Sci., 29, pp. 797-800 (1972).

*Program information and data cards were kindly provided by Dr. Michael Weinreb and Larry McMillan of the NOAA/NESS.

pertinent data cards for use with the NOAA transmittance routines. One of the NOAA subroutines generates a first-guess water vapor profile by a regression technique that depends on the initial temperature profile and the geographical location. This routine was prepared for computer use to provide the water vapor distribution for water vapor transmittance computations. Another NOAA routine that provides a constant ozone transmittance correction also was adopted. Thus, the overall NOAA transmittance routine, which includes temperature corrections based on the initial temperature profile, was applied in both of the retrieval methods. However, slant-path corrections were introduced for each specific retrieval area, since these areas did not coincide with those used operationally by NOAA. Except for the surface temperature and the initial profile of atmospheric temperatures, the Minimum Information technique employed was the NOAA technique. In addition, the NOAA "CLRAD" routine for generating equivalent clear column radiances from measurements over a partly cloudy area encompassing 64 scan spots was prepared for limited application over land.

The computer program for the Linear Direct retrieval method was interleaved with the program for the Minimum Information method. Thus, both retrieval methods were applied together, using the same transmittance representations and input information. Data for the applications were selected on the basis of an examination of the mosaic images of the NOAA-2 scanning radiometer for mid-June 1973. Digital data tapes covering 48 hours of VTPR measurements, North American rawinsonde data tabulation for the same period, and synoptic surface maps were obtained from the National Environmental Data Service, Asheville, North Carolina. Pertinent radiance data over the United States were recopied on a working tape from which batch listings for the eight VTPR channels were prepared for closer inspection.

Twelve land areas were selected for temperature retrievals by both methods. The geographical location and size of these areas are illustrated in Figure 13 together with the pertinent subsatellite tracks. The two poleward tracks indicated by solid lines, separated in time by about 2 hours, demonstrate the spacing between successive evening (local time) satellite overflights. The two dashed tracks illustrate subsatellite positions for two swaths (one evening and one the following morning) that intersect in a region generally free of clouds at both times. Areas numbered 1 through 10 on Figure 13 refer to regions apparently free of clouds. Area 11 refers to a region with a mixed sky cover, whereas Area 12 is located over a region with an apparent dense cloud undercast. The clear region encompassing retrieval Areas 4 through 7 and the dense undercast in retrieval Area 12 are apparent in the ATS photograph shown in Figure 14. Figure 15 is a copy of the infrared mosaic from the scanning radiometer data of the NOAA-2 satellite for the evening of 13 June 1973 (early morning Greenwich time on 14 June). This figure shows how the clearing had extended to the North Atlantic states and illustrates the type of cloudiness over retrieval Area 11.

Emphasis was given to retrievals over clear land areas to avoid unnecessary cloud contamination of the radiances and to enable radiometric estimates of the boundary surface temperature. Clear-area retrievals were attempted in clusters, with two clusters in the same general region, to enable some initial assessment of spatial and temporal temperature gradients derived from retrievals in the general vicinity of rawinsonde stations. One clear area (Area 6) was introduced to assess sensitivity of the retrieval profile to the proper boundary condition for slightly elevated terrain. Area 11 was introduced to check out the CLRAD program over land and Area 12 was introduced to check the possibility of applying the retrieval routines only to the atmospheric portion above an opaque cloud layer at high altitudes.

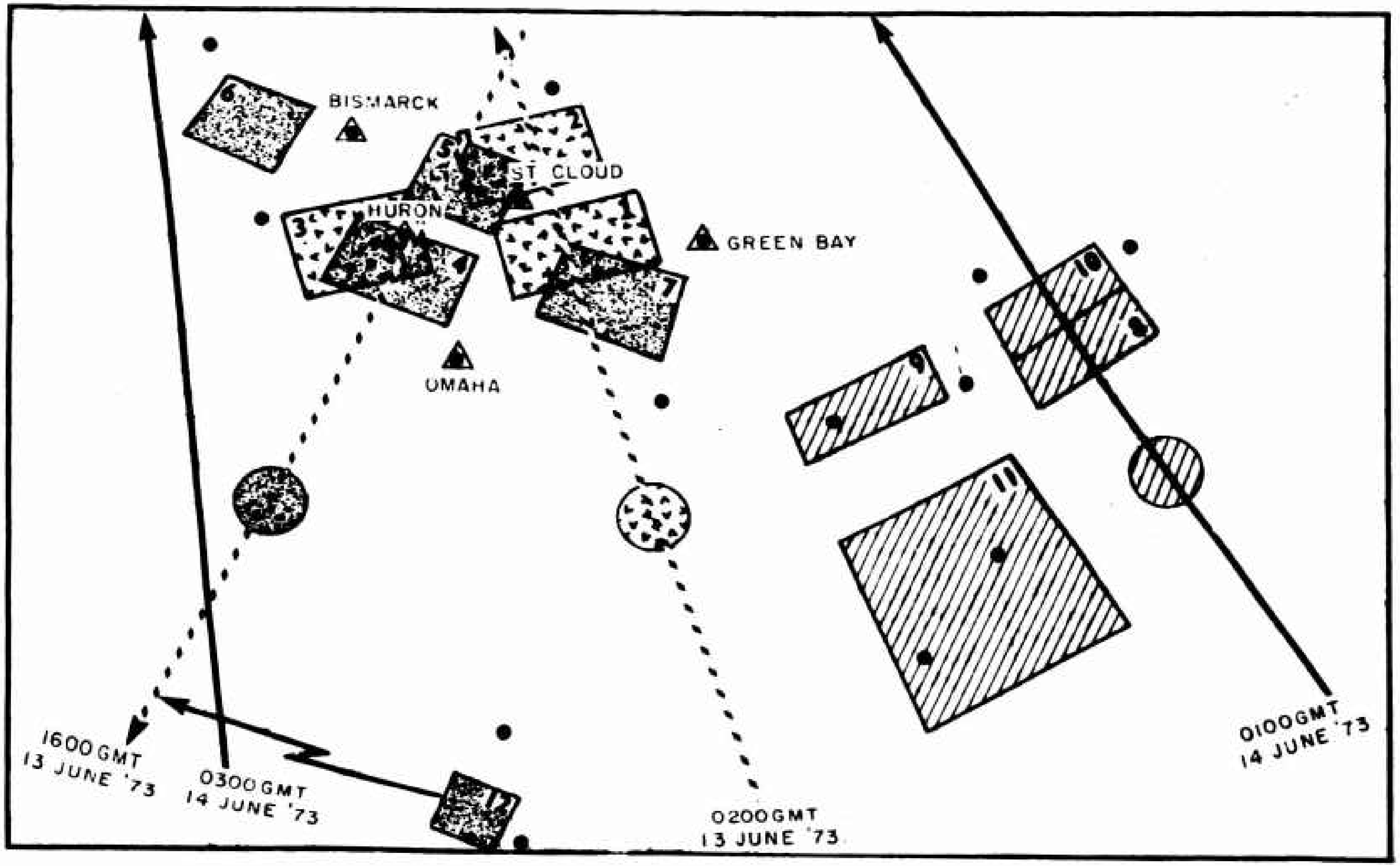

FIGURE 13 LOCATION OF SELECTED NOAA-2 SUBSATELLITE TRACKS IN JUNE 1973 AND AREAS OF TEMPERATURE RETRIEVALS FOR VTPR MEASUREMENTS (HEAVY DOTS INDICATE LOCATIONS OF NEARBY RAWINSONDE STATIONS)

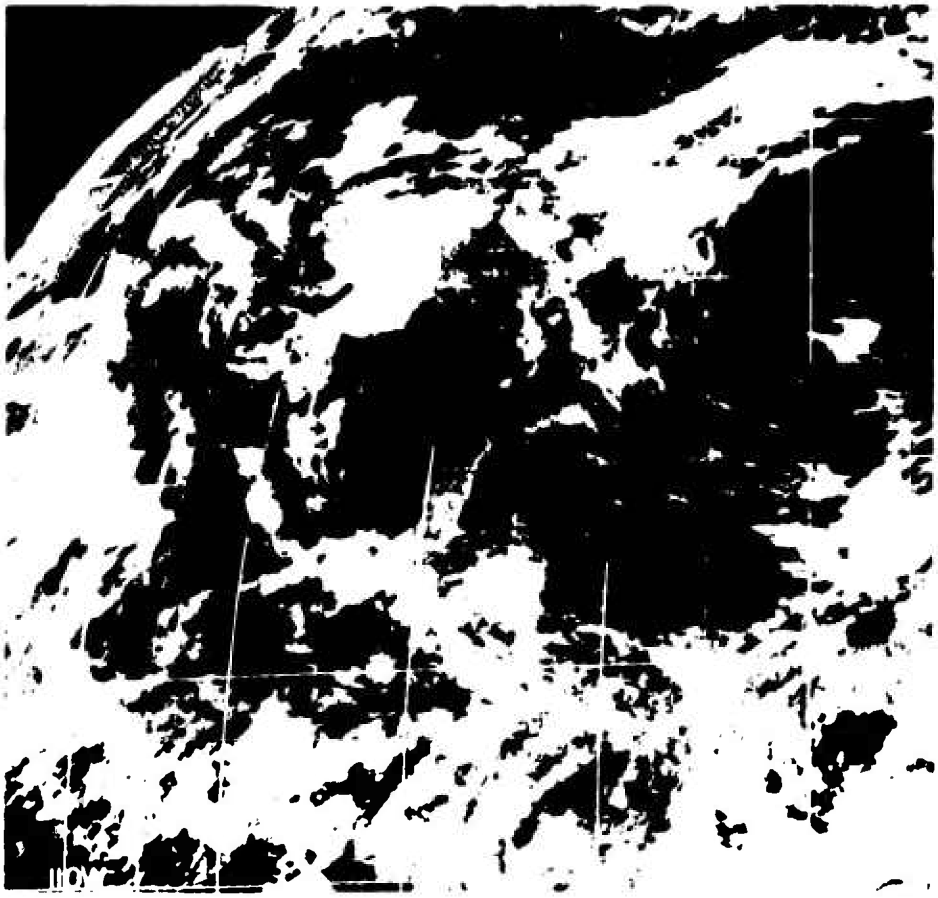

FIGURE 14 ATS-3 CLOUD PHOTOGRAPH FOR 1519 GMT, 13 JUNE 1973

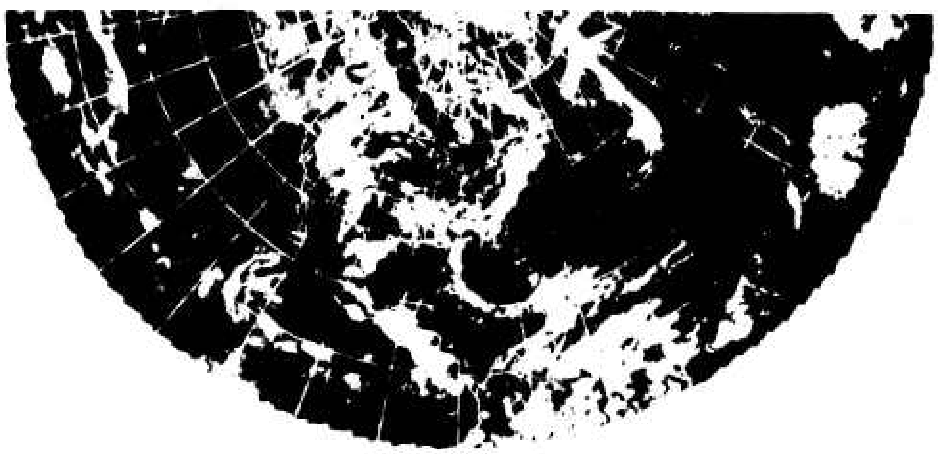

FIGURE 15 PORTION OF DIGITIZED INFRARED MOSAIC FOR 2100 LST, 13 JUNE 1973 (FROM NOAA CATALOG OF SATELLITE IMAGERY, KMRD NO. 5.4, JUNE 1973)

No retrievals of water vapor profiles were attempted; the first-guess water vapor profile based on the NOAA regression technique was held fixed during each retrieval. The first-guess temperature profile for all retrievals by both methods was taken as the standard mid-latitude summer profile presented by McClatchy et al.[12] For one area (Area 2) the first-guess temperature profile also was revised to correspond to nearby rawinsonde profiles. In the absence of forecast initial temperature profiles, it was considered that the use of the same initial profile for all retrievals was best suited for an evaluation of results, since the retrievals themselves depend in part on the initial profile.

NOAA routines for handling 100 data levels between 0.1 mb and 1000 mb were modified to accept a lower boundary with an arbitrary pressure (elevation), as indicated by the surface data. Printouts of the radiance data were used to select the final retrieval areas for the clear regions and for the region with a homogeneous dense undercast. Radiances enclosed by the clear target boundaries were averaged to define the appropriate clear-column radiances required in the retrievals. The window channel (Channel 8) VTPR data were used to define the surface temperature. Sample computations indicated that over the clear areas the measured window channel equivalent temperature had to be increased by 4°K to compensate for atmospheric attenuation (atmospheric attenuation was neglected over the high, dense undercast of Area 12). The early evening surface temperatures required for the retrieval in the partly cloudy Area 11 were determined from standard surface (shelter) observations.

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[12] R. A. McClatchey et al., "Optical Properties of the Atmosphere (Revised)," Environmental Research Papers No. 354, Air Force Cambridge Research Laboratories, L. G. Hanscom Field, Bedford, Massachusetts, May 1971.

2. Results

In almost all of the retrievals the NOAA Minimum Information method gave the best results, both in terms of computer time and in shape of the profile. The generally superior profile shape may have resulted from the strong tendency of the retrieval profile to cling to the first-guess shape throughout much of the atmosphere. The poor convergence rate (relatively long computer time) of the Linear Direct method resulted from frequent need to employ an adjusted algorithm close to the Smith 1970 algorithm because of excessive overshoot in the proposed algorithm.

Figure 16 illustrates the results of the Minimum Information retrieval for Clear Area 1. The short-dashed line represents the initial-guess temperature profile, the solid line represents the retrieved profile, and the points connected by long dashes describe the observations at the rawinsonde station closest in space and time. The same features are illustrated in subsequent diagrams.

Figures 17a and 17b illustrate the retrievals by both methods for Clear Area 2, based on the same standard atmospheric temperature profile for the first guess. The inferiority of the Linear Direct method is apparent. However, the poor profile illustrated for the Linear Direct retrieval results in part from the failure of the method to converge to an acceptable solution after 9 iterations. Nevertheless, the retrieved profile is characteristic of problems with the Linear Direct retrieval in that the temperature gradient between the mid and upper troposphere is too unstable (cold near tropopause, warm in mid-troposphere). In contrast, the stability usually is too large in the lower troposphere. Thus, a smoothed version of the Linear Direct retrieval probably would represent a reasonable solution with an acceptable stability distribution. Figures 17c and 17d illustrate, for both methods, retrievals that result from a change in the initial-guess temperature profile. Here the first guess is

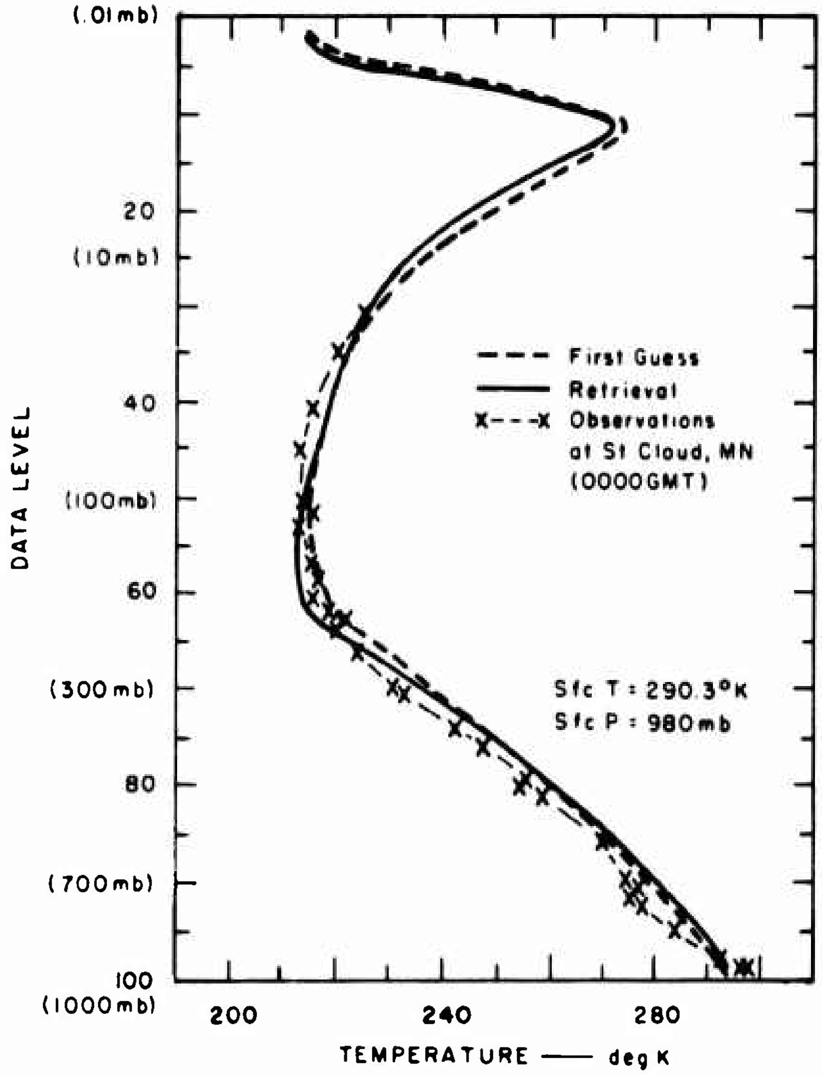

FIGURE 16 FIRST-GUESS, RETRIEVAL, AND NEARBY OBSERVATION OF TEMPERATURE PROFILE FOR NOAA-2 VTPR DATA AREA 1 (CLEAR SKIES), 0216 GMT, 13 JUNE 1973 (SEE FIGURE 13 FOR LOCATION OF RETRIEVAL AREA)

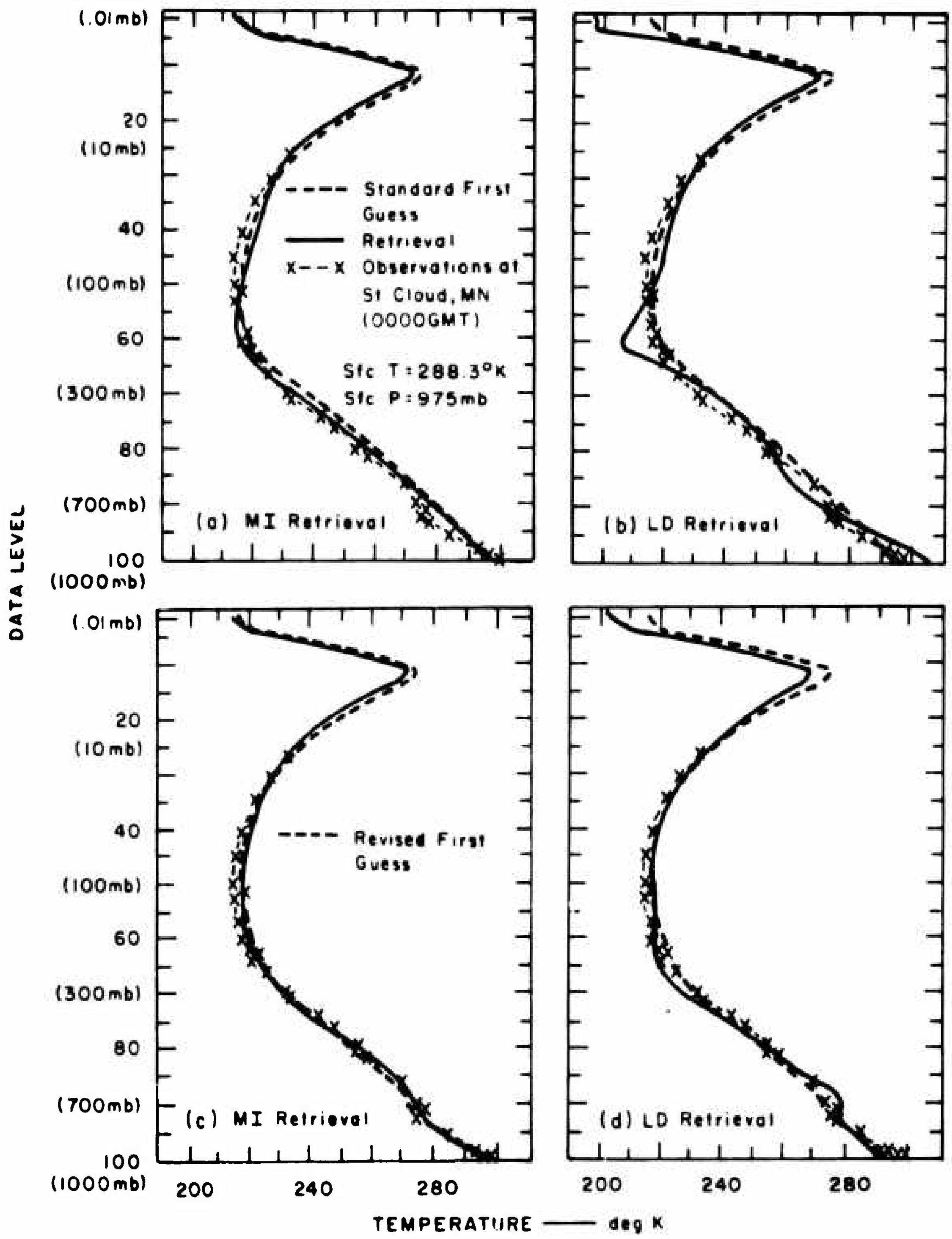

FIGURE 17 TEMPERATURE RETRIEVALS BY MINIMUM INFORMATION (MI) AND LINEAR DIRECT (LD) RETRIEVAL METHODS USING STANDARD AND REVISED FIRST-GUESS PROFILES OVER VTPR DATA AREA 2 (CLEAR SKIES), 0216 GMT, 13 JUNE 1973

designed to represent observed conditions rather than a standard profile. Of course, the temperature points from observed soundings that are close in space and time do not necessarily represent the "true" profile. At any rate, with the improved first guess the retrievals also are improved for both methods. The Minimum Information method now captures the small stable layer in the lower atmosphere. This same feature is greatly exaggerated by the Linear Direct method. The latter retrieval, which now converges to a solution, still shows a relatively unstable upper troposphere. Since both methods converged to particular solutions, it is disturbing to note that the two solutions do not agree. This result merely demonstrates the nonuniqueness of the retrievals, with the particular solution by the Minimum Information method remaining closest to the initial guess.

Figure 18 illustrates retrievals by the Minimum Information method for Clear Area 6, first with the true lower boundary at 915 mb and, second, with the lower boundary assumed to exist at the lowest data level (1000 mb). It is apparent that such changes in the elevation of the lower boundary have no significant influence on the retrieval. In both cases, the surface temperature inversion is not captured by the retrieval. Some uncertainty in the retrieval process near the lower boundary could result from the strong influence of water vapor on the response through VTPR Channel 6, the most transparent spectral region for CO_2.* In fact, the total water vapor transmittance down to the surface in this spectral region, for the adopted water vapor distribution, actually is less than the carbon dioxide transmittance. Of course, the real atmosphere may have been drier than that postulated by the first-guess water vapor profile. However, the strong influence of water vapor tends to increase the transmittance weighting function near the boundary layer; therefore, the water vapor transmittance is not likely to cause the insensitivity of the retrieval near the

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*The six VTPR retrieval channels are centered approximately at 667, 678, 695, 708, 725, and 748 cm^{-1}, respectively.

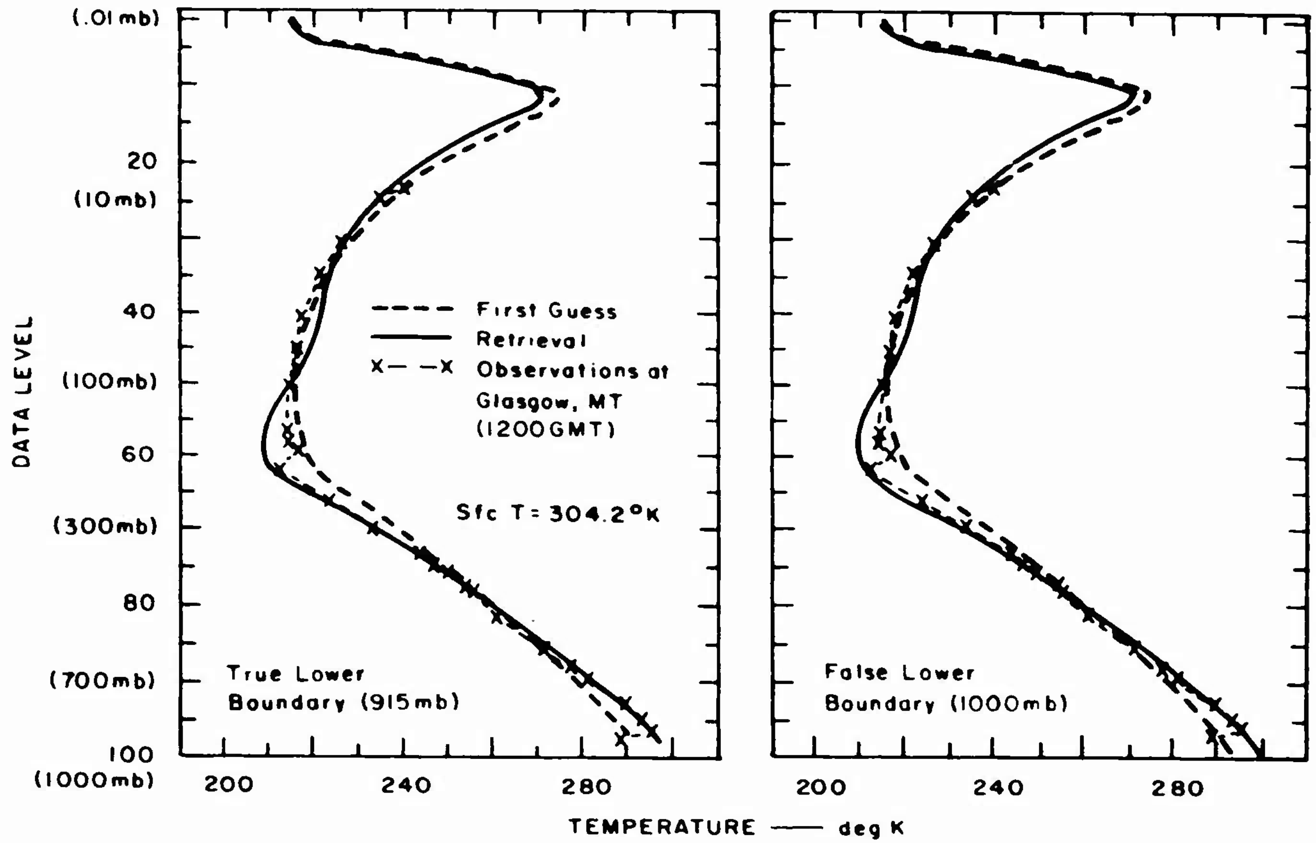

FIGURE 18 TEMPERATURE RETRIEVAL FOR VTPR DATA AREA 6 (CLEAR SKIES), 1609 GMT, 13 JUNE 1973, WITH TRUE LOWER BOUNDARY (915 mb) AND FALSE LOWER BOUNDARY (1000 mb)

surface. On the other hand, without any consideration of water vapor, the retrievals would be unsatisfactory.

Figure 19 shows the results of retrievals by both methods over the dense undercast of retrieval Area 12. In accordance with the uniform measurements in the window channel (Channel 8), the boundary temperature was set at 212.4°K and assigned a pressure of 190 mb (between data levels 61 and 62). It is possible that this data level and pressure were in error, i.e., a lower pressure may have been more appropriate. In any event, the Minimum Information method failed to produce a satisfactory result (after two iterations) for the profile above this high-level boundary. The Linear Direct method, after 9 iterations, tended to produce a reasonable profile. Neither of the methods had converged to an acceptable solution. Although part of the difficulty may have been due to an erroneous boundary definition, it was concluded that the major problem was associated with the weighting functions for Channels 4, 5, and 6. With such an elevated boundary, these spectral regions correspond to window regions; the retrieval probably should have been restricted only to measurements in the first three channels.

Figure 20 illustrates the derived temperature profile by the Minimum Information method for retrieval Area 11. Computer time was increased by use of the NOAA CLRAD program. In view of the extensive cloudiness over the area, the generation of radiances without cloud contamination and the temperature profile retrieval appear to have been successful, or at least comparable to retrievals in areas that were clear. Additional inprovement could have been accomplished with a different first-guess temperature profile.

To examine spatial gradients and time changes of retrieved temperature data and to compare results with corresponding quantities derived from nearby rawinsonde observations, portions of each temperature

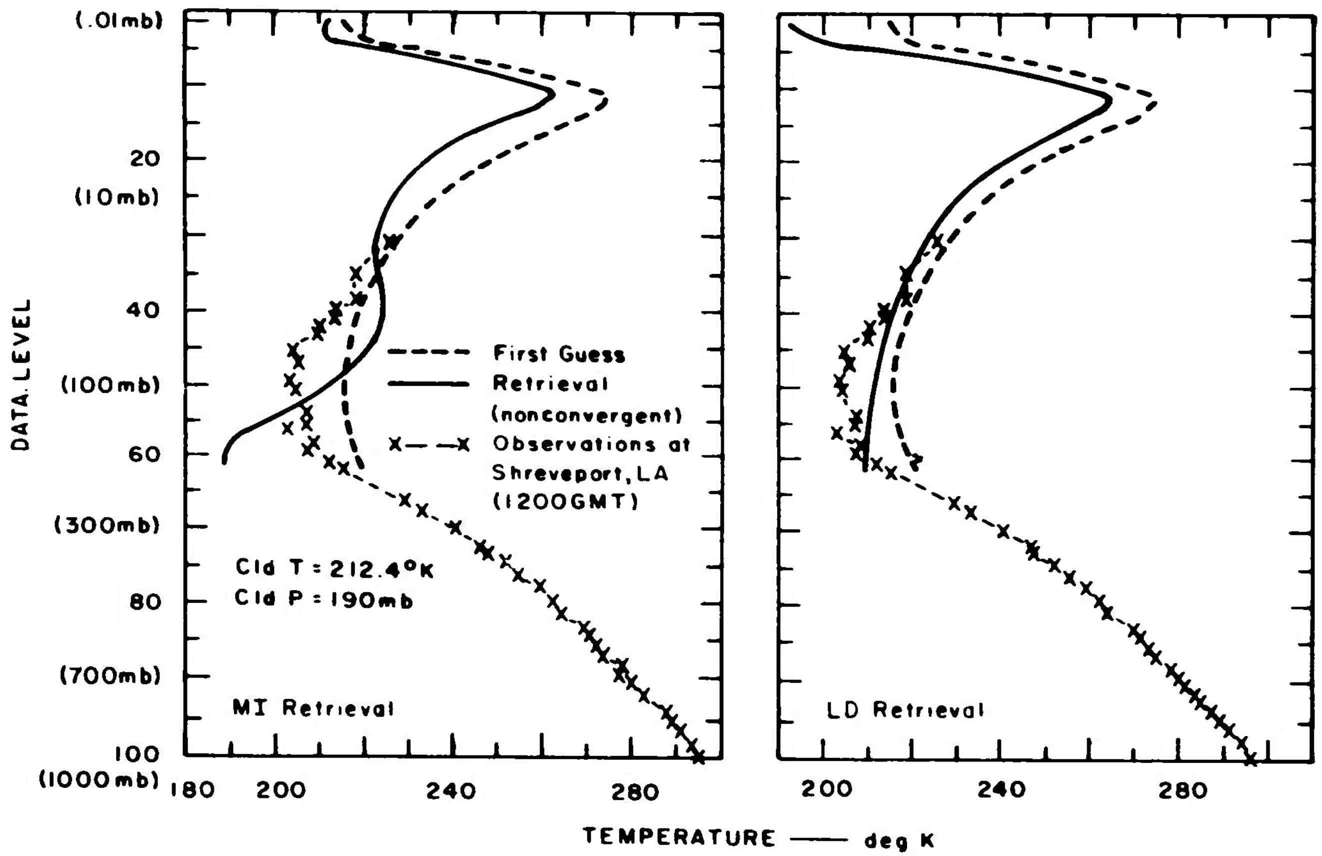

FIGURE 19 NONCONVERGENT TEMPERATURE RETRIEVALS BY MINIMUM INFORMATION (MI) AND LINEAR DIRECT (LD) RETRIEVAL METHODS FOR ATMOSPHERE ABOVE A UNIFORM OPAQUE CLOUD UNDERCAST AT THE 190-mb PRESSURE LEVEL, VTPR DATA AREA 12, 1612 GMT, 13 JUNE 1973

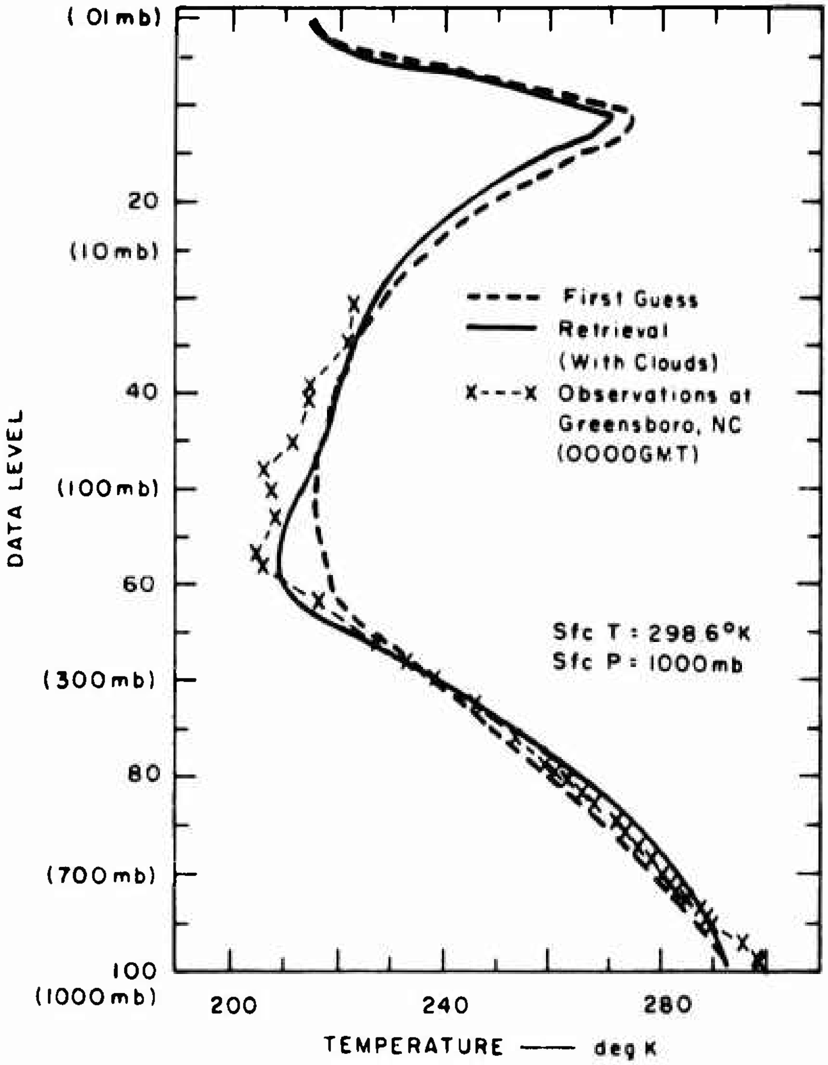

FIGURE 20 TEMPERATURE RETRIEVAL BY MINIMUM INFORMATION METHOD FOR REGION WITH CONSIDERABLE CLOUDINESS OVER VTPR DATA AREA 11, 0113 GMT, 14 JUNE 1973

sounding were divided into three layers (850 to 700 mb, 700 to 500 mb, and 500 to 300 mb) and mean temperatures were determined for each layer. Layer-averaged temperatures were then analyzed over a triangular array of locations to define a triangle mean (the arithmetic average of the layer averages from the three locations) and the W-E and S-N temperature gradients on the basis of a first-order Taylor series expansion about the triangle center. Two triangular arrays were formed by the retrievals over

Areas 1-2-3 (at 0200 GMT, 13 June 1973) and Areas 4-5-7 (at 1600 GMT, 13 June 1973). Corresponding triangular arrays on two scales were formed by the rawinsonde observations at Omaha, Nebraska--Huron, South Dakota--St. Cloud, Minnesota; and Omaha, Nebraska--Bismark, North Dakota--Green Bay, Wisconsin. The latter array covers an area slightly larger than the retrieval array area, whereas the center for the smaller array is slightly misplaced relative to the retrieval areas. Rawinsonde temperature profiles were analyzed at 0000 GMT and 1200 GMT on 13 June 1973 as well as 0000 GMT on 14 June 1973 to enable interpolation of the triangle means and gradients to the times of the retrievals. It was assumed that differences in radiation-induced temperature errors were negligible for the observed soundings, and that cloud contamination was absent in the retrieval soundings.

Results of this analysis for the 300 to 500 mb and 500 to 700 mb layers are summarized in Table 2. The results for the 700 to 850 mb layer are not included. However, the discrepancies between retrievals and observations are more pronounced for this layer, presumably because of the insensitivity of the retrieval to the detailed thermal and moisture structure as the lower boundary is approached.

Satisfactory agreement between mean layer temperature and their height gradients and time changes generally exists between retrieved and observed data. The smaller scale (scale I) of rawinsonde observations leads to the best overall agreement with retrieved data. These results are encouraging in light of the fact that the same standard profile was used as the initial guess for all retrievals; aside from the radiometric estimates of surface temperature, no a priori information or forecast data were introduced as input. Thus, the results are obtained independently of possible improvements with altered first-guess profiles.

Table 2

SPATIAL AND TEMPORAL CHANGES IN MEAN LAYER TEMPERATURES OVER SOUTHWESTERN MINNESOTA FROM TRIANGULAR ARRAYS OF (a) VTPR RETRIEVALS AND (b) NEARBY RAWINSONDE (RW) OBSERVATIONS
13 June 1973

Layer:	Array*	0200 GMT	1600 GMT	14-Hour Change
MEAN LAYER TEMPERATURE (°K)				
300-500 mb:	Retrieval	248.9	250.9	+2.0
	RW Scale I	248.6	249.5	+0.9
	RW Scale II	248.9	248.8	-0.1
500-700 mb:	Retrieval	269.1	271.3	+2.2
	RW Scale I	269.1	270.3	+1.2
	RW Scale II	269.2	270.3	+1.1
WEST-EAST GRADIENT (°K/deg lat)				
300-500 mb:	Retrieval	0.15	0.27	0.12
	RW Scale I	-0.33	-0.06	0.27
	RW Scale II	-0.05	-0.44	-0.39
500-700 mb:	Retrieval	0.15	0.13	-0.02
	RW Scale I	0.21	0.04	-0.17
	RW Scale II	-0.09	-0.30	-0.30
SOUTH-NORTH GRADIENT (°K/deg lat)				
300-500 mb:	Retrieval	-0.55	1.07	1.62
	RW Scale I	-1.29	-0.91	0.38
	RW Scale II	-0.95	-0.89	0.06
500-700 mb:	Retrieval	-0.73	1.14	1.87
	RW Scale I	-0.92	-0.81	0.11
	RW Scale II	-0.71	-0.56	0.15
HEIGHT GRADIENT (°k/200 mb)				
Layer	Retrieval	-20.2	-20.4	0.2
Difference	RW Scale I	-20.5	-20.8	0.3
	RW Scale II	-20.3	-21.5	1.2

*Arrays (see Figure 13)
0200 GMT Retrieval: VTPR Areas 1, 2, and 3
1600 GMT Retrieval: VTPR Areas 4, 5, and 7
RW Scale I: Omaha, Nebraska - Huron, South Dakota - St. Cloud, Minnesota
RW Scale II: Omaha, Nebraska - Bismark, North Dakota - Green Bay, Wisconsin.

Comparisons of the retrieved and observed horizontal gradients cannot be considered satisfactory. Of course, the horizontal gradients are small and rather ill defined for the type of synoptic situation experienced. Retrieval West-East gradients and their time changes appear to relate better to the observations on scale I, but for the 300 to 500 mb layer there is a difference in the sense of the small gradients. Retrieved South-North gradients at 1600 GMT show a reversal of the gradient retrieved at 0200 GMT. This reversal disagrees with gradients determined from observations on both scales. Since the South-North gradients are significant and since the observed results on both scales are consistent, the disagreement at 1600 GMT cannot easily be dismissed. If the retrieved South-North gradient at 1600 GMT are in error, the use of identical initial-guess temperature profiles and fixed water vapor profiles at all retrieval locations could have been responsible.

F. Recommendations for Additional Retrieval Study

In general, applications of retrieved temperature profiles have been hampered by nonuniqueness of solutions and the lack of truly reliable evaluation data. Difficulties with particular techniques have been associated with cloud "contamination" of radiances, restrictive first-guess profiles (including the boundary temperature), and uncertainties in the accuracies of transmittances.

A reasonable first step in retrieval over land would be an initial interpretation of synoptic circulation and cloud features based on patterns observed in time-lapse imagery. Homogeneous retrieval areas then should be selected and identified as clear, partly cloudy, or undercast. For the latter category, some estimate must be made of the opaque boundary pressure (based on some standard atmosphere) and the number of channels to be included in the retrieval for the atmosphere above the undercast. Window channel radiances can be used to define the lower boundary temperature

for clear areas, but upward adjustments in temperature should be based on the apparent type of air mass and the surface pressure. Surface pressures, in turn, might be estimated from the terrain elevation, the apparent synoptic circulation, and interpolation-extrapolation of available surface pressure observations. Similarly, for partly cloudy areas, the initial estimate of surface temperature might be based on interpolation-extrapolation of available surface temperature observations (or window radiances in surrounding clear areas) in conjunction with the inferred synoptic patterns. First-guess atmospheric profiles of temperature and humidity could be based on standard models with deviations prescribed empirically in terms of the synoptic patterns.

An overall effort to improve retrieval procedures in cloudy areas is needed; recent progress has been made in this direction.[16] Furthermore, post-retrieval empirical modification of profiles should be considered, providing that radiances are not altered, to establish the limits for possible small-scale features not captured in the retrieval. The information content in the departures of retrievals from first guesses should be explored more fully, but it is preferred that the retrieved solution should not be tied too closely to the first guess. Any revised retrieval procedure should be competitive, in terms of computer time, with the Minimum Information method of NOAA.

Improved retrieval routines should incorporate water vapor retrievals with the temperature profile retrievals. Realistic physical constraints should be imposed internally; for example, superadiabatic lapse rates or supersaturation should not be allowed. The lower boundary temperature should be allowed to vary within limits during each iterative stage. Transmittance representations for routine application should be improved

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[16] R. Jastrow and M. Halem, "Accuracy and Coverage of Temperature Data Derived from the IR Radiometer on the NOAA 2 Satellite," J. Atmos. Sci., 30, pp. 958-964 (1973).

and transmittances recomputed with each iteration. Representations should be "calibrated" by statistical comparisons of measurements with radiance computations for observed atmospheric conditions. For the retrieval mechanics a nonlinear direct (iterative) approach appears to be attractive. An adjustment algorithm that employs ratios instead of a linear adjustment offers the possibility of reasonably rapid convergence without serious undershoot to the revised Planck functions. Scaling to a reference wave number probably should be included if possible; the number of data levels could be reduced significantly from the 100 used by NOAA, and the spacing of data levels could be altered.

IV CLOUD MOTION VECTOR (CMV) ANALYSIS SUBTASK

A. Objectives of the Cloud Motion Vector Analysis Subtask

There are three basic objectives of this subtask:

(1) To determine the computer size and time constraints for the calculation of CMV's in support of the other subtasks of this project.

(2) To compare CMV measuring techniques.

(3) To postulate a potential registration and gridding scheme and identify potential problems.

It is not an objective of this subtask to compute or measure cloud motion vectors. Neither is it within the scope of this work to extend the landmark registration or gridding programs. It is the intent of this report to give the current state of the art in CMV analysis without attempting to extend this state of the art. It is also the intent of this report to point out some areas where further work is necessary.

B. Technical Approach to the CMV Analysis Subtask

The technical approach to this subtask has been to draw from previous experience at SRI gained from on-going research in the field of cloud motion vector analysis. No CMV computations were performed directly for this project. Our efforts here have been to summarize, compare, and draw conclusions from previously collected data.

1. Program Sizes and Execution Times

Program sizes and execution times were logged for selected runs with typical data for various tasks on SRI Project 2005 for NASA.[17] For these runs, it took an average of 81 central processor (CP) seconds and 103 peripheral processor (PP) seconds on SRI's CDC 6400 Computer to process one area for a pair of frames. The CP time is a measure of the amount of actual computations performed and the PP time shows the amount of input/output activity.* These times were derived from a relatively small sample of actual executions of the current version of the SRI objective system for computing cloud motions, which uses the clustering technique. There are four programs that make up this system, which range in size from 20,000 to 34,000 (decimal) words of CDC 6400 core storage (each word is 60 bits long).

Considerable printout was obtained since it was desired to monitor each program. In a production environment, this quantity of printout would be undesirable, and considerable computer time can be saved.† Because our projects have been primarily concerned with feasibility, little effort has been expended on optimizing the programs for either minimum size or execution times. All the programs are coded in FORTRAN. Elimination of most of the printout alone would cut execution time by almost 50 percent. <u>Times in this report will be given without estimating this cut</u>.

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[17] D. E. Wolf, D. J. Hall, A. R. Tobey, and R. G. Hadfield, "Development of an Automatic Computer System for Measuring Cloud Motion Vectors," Final Report, NASA Contract NAS5-21776, Stanford Research Institute, Menlo Park, California (September 1973).

* This is approximate. For example, printing, an input/output operation, requires formatting of the text that is printed; formatting is a CP operation. However, the above categorization will serve the purposes of this report.

† This will also help to reduce the core storage requirements as some storage is used only for printing.

In this report, it is assumed that the bulk of the CMV analysis will be done by a computational method. This assumption is justified by past experience and our assessment of the probable development of computational methods. It is further assumed that either of the two computational methods, correlation or cluster analysis (for which the previous times were given), will take comparable* execution times (and core sizes) to get an equal number of CMVs. Thus, times will be given for the clustering method and will be considered as typical for the correlation method also.

CMVs must be given on a one degree grid over a 50 by 50 degree area to make a 48-hour forecast for an area of interest to the Army operations (see the section of the report on Prognosis). Using the same resolution (about 6 miles per element, hence a minimum of 60 miles between CMVs) as the previously mentioned project, it would take about 1 hour to compute about 800 CMVs over the 50 by 50 degree area. Editing and grid point analysis of the CMVs using the wind Editing and Analysis Program (WEAP-IA)[15] would take less than one-half hour. Thus, the total time to compute CMVs, including grid point analysis on a one degree grid, for a 58-hour forecast would take less than 1.5 hours.

While most minicomputers have a basic cycle time comparable to the CDC 6400, floating point arithmetic on a minicomputer typically uses two words per value and hence uses two cycles to fetch a value. Thus,

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*However, a hardware device for computing correlations could make the correlation method faster. See the comparisons section for a more thorough discussion of this.

[15] R. L. Mancuso, and R. M. Endlich, "Wind Editing and Analysis Program-Spherical Grid (WEAP-IA)," Users Manual, U.S. Army Research Office, Durham Contract DAHC04-71-C-0013, Stanford Research Institute, Menlo Park, California (February 1973).

programs such as used for CMV analysis can be expected to run slower on the minicomputer. Also, a floating point array would use twice as many words on the minicomputer as on the CDC 6400, so storage requirements on the minicomputer would be increased considerably. With a minimum effort type of conversion of the existing programs to a minicomputer, the programs could be expected to take less than 5 minutes per area and use about 50,000 words of core storage. By using more effort on the conversion, such as using integer arithmetic in place of floating point, and coding some of the routines in machine language, these requirements might be reduced to under 1.5 minutes per area and 32,000 words.

2. Comparison of CMV Measurement Systems

The comparison of CMV measurement systems is broken into two parts: a comparison of CMV measurement methods and a comparison of CMV measurement results using the various methods. Before any comparisons can be made, a brief description of each method is in order.

The different methods can be broken down into two basic types depending on whether the data are used in pictorial form or in digital form. Those using pictorial data will be called visual methods and those using digital data will be called computational.

Two types of visual methods are the film loop technique[19,20] and the SRI cloud console technique.[21] For the film loop technique, each frame of a sequence of pictures is repeated several times on a piece of

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[19] L. F. Hubert and L. F. Whitney, Jr., "Wind Estimation from Geostationary-Satellite Pictures," Mon. Wea. Review, Vol. 99, No. 9, pp. 665-672 (1971).

[20] T. D. Fujita, D. L. Bradbury, C. Murino, and L. Hull, "A Study of Mesoscale Cloud Motions Computed from ATS-I and Terrestrial Photographs," SMRP Research Paper 71, University of Chicago, Chicago, Ill. (1968).

[21] S. M. Serebreny, E. J. Wiegman, R. G. Hadfield, and W. E. Evans, "Electronic System for Utilization of Satellite Cloud Pictures," Bull. Amer. Meteor. Soc., Vol. 51, No. 9, pp. 848-855 (1970).

film, these pieces of film are spliced together, and finally the two ends are joined to make an endless loop. This loop is then projected onto a digitizing board so that a man can measure the location of a cloud in as many frames as possible. The difference in these locations gives the cloud motions.

The SRI cloud console (ESIAC - Electronic System for Image Analysis) can be thought of as a closed-circuit television playback device. The pictures are "read in," using a closed circuit TV camera and stored on a video disk. A man can play the pictures back on a monitor and observe motions, thus obviating the need for film loops. Movable x and y cursors allow the man to measure the location of a cloud in any frame, the difference of the locations of the same cloud in successive frames gives the motion vector.

The computational methods of CMV analysis are of two basic types: the cross-correlation techniques and the clustering approach. In the NOAA System[22] (a cross-correlation technique), a small array of picture data is selected without regard to content from specified locations on a regular grid. These data from picture one are matched on picture two by finding the location giving the highest cross correlation. The motion that is recorded is the difference in locations at the two times. The other correlation technique, the University of Wisconsin System[23] also uses cross correlation to find the location of data from picture one in the second picture. It uses a man to visually select data from

[22] J. A. Leese, C. S. Novak, and B. B. Clark, "An Automated Technique for Obtaining Cloud Motion from Geosynchronous Satellite Data Using Cross Correlation," J. Appl. Meteor., Vol. 10, No. 1, pp. 118-132 (1971).

[23] E. A. Smith and D. R. Phillips, "Automated Cloud Tracking Using Precisely Aligned Digital ATS Pictures," Proceedings, Two-Dimensional Digital Signal Processing Conference, Columbia, Missouri, 26 pp. (October 1971).

picture one that contains a cloud or portion of a cloud. Note that this method uses the data in both pictorial and digital form. It is included as a computational method because the motions are actually determined from the digital data using a cross-correlation computation.

The SRI objective technique[24] consists of thresholding the brightness data so points that represent clouds are separated from the background, and then using a general purpose cluster analysis program (ISODATA) to identify centers of brightness within these clouds. Measures of size, shape, brightness, and location are computed for each center. Finally centers of brightness from two consecutive times are paired so as to minimize the change in size, shape, and brightness. The cloud motion vector is then recorded from the center at the first time to the center at the second time.

C. Comparison of Cloud Motion Measurement Results Using Various Techniques

As mentioned previously, the work on SRI Project 2005 (Contract NAS-5-21776) included comparisons of CMVs measured on common data sets by different techniques.[25] Two different data sets were used. ATS-III data from 23 August 1969 were used as a basis for comparing CMVs measured by the SRI Objective Technique and the ESIAC. The other data set, ATS-I data from 15 August 1972, was used as a basis for comparing CMVs measured

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[24] R. M. Endlich, D. E. Wolf, D. J. Hall, and A. E. Brain, "Use of a Pattern Recognition Technique for Determining Cloud Motions from Sequences of Satellite Photographs," J. Appl. Meteor., Vol. 10, No. 1, pp. 104-117 (1971).

[25] D. E. Wolf, D. J. Hall, A. R. Tobey, and R. G. Hadfield, "Development of an Automatic Computer System for Measuring Cloud Motion Vectors," Final Report, NASA Contract NAS5-21776, pp. 33-52, Stanford Research Institute, Menlo Park, California (September 1973).

by the SRI Objective technique and the NOAA Correlation technique. The results of these comparisons are summarized here.

1. SRI Cloud Console (ESIAC) Versus SRI Objective Methods

To get the most direct possible comparison of measurements of cloud motions using SRI's objective system and measurements by a human using SRI's ESIAC, facsimile pictures were made from the digital tapes on SRI's XDS 930 computer. Grid lines were included by making every 300th column and 100th row white.

The pictures were registered on the grid lines when they were entered on the disk of the ESIAC, leaving landmarks free to move in the frames. This movement was measured and compared with apparent landmark motions calculated by objective means for the same landmark. Very good agreement was achieved for this comparison when measurements made on the ESIAC by several operators were averaged together. As the objective landmark registration uses correlation,[28] this gives a limited comparison between correlation and the ESIAC. Landmark registration will be covered in more detail later in this report.

To give the best possible comparison between CMVs measured with the two techniques, no attempt was made to compensate for apparent landmark motion. Thus, CMVs measured by either technique are biased by exactly the same amount. As long as the motions are smooth, this gives a valid comparison of the measurements of observed cloud motions. It should be noted, however, that while a trained meteorologist can make measurements

[28] D. E. Wolf, R. M. Endlich, and D. J. Hall, "Further Development of Objective Methods for Registering Landmarks and Determining Cloud Motions from Satellite Data," pp. 7-16, Scientific Report, U.S. Navy Contract N62306-71-C-0068, Stanford Research Institute, Menlo Park, California (September 1972).

on cloud tracers, he may lose his insight of the meteorology of the region, if the distortions are large, by not working with registered pictures.

To convert from cloud console units to tape coordinates, measurements were made on the grid lines that appeared in a scene. A least-squares approach was used to calculate transformation coefficients for the conversion. All comparisons are made in modified tape coordinates. Tape coordinates are 8,192 columns on each of 2,400 lines. To get closer resolution in both directions, the column numbers have all been divided by three.

An area off the coast of Africa, with primarily a single layer of cloud motion, was selected for the comparison. Sixty-six tracers were identified, and the location of each tracer in as many of five frames as possible was measured by a human using SRI's cloud console (ESIAC). Six applications of the objective system, using a 6 column by 2 row unit size, were used to cover the same area, giving 410 motion measurements on 207 tracers. Note that the average tracer that the human picks persists over all five frames, while the average tracer that the objective system picks persists over three frames. Figure 21 shows the motions for a typical pair of frames, with a "C" denoting cloud console motions and an "I" denoting automatic (ISODATA) motions. Table 3 gives a summary of the differences between each objective motion vector and the closest cloud console motion. ΔU is the difference in the east-west components of the motions (positive to the east); ΔV is the difference in the north-south components of the motions (positive to the south). For both, the value of the objective system vector was subtracted from the value of the corresponding cloud console vector, so a negative value implies the vectors of the objective system are generally larger (or more positive). The other columns are: the absolute angular difference ($|\Delta\theta|$), magnitude of the vector difference (|Vector Difference|), and absolute value of the difference in magnitude (|Difference in Magnitude|). The top line gives the average for each

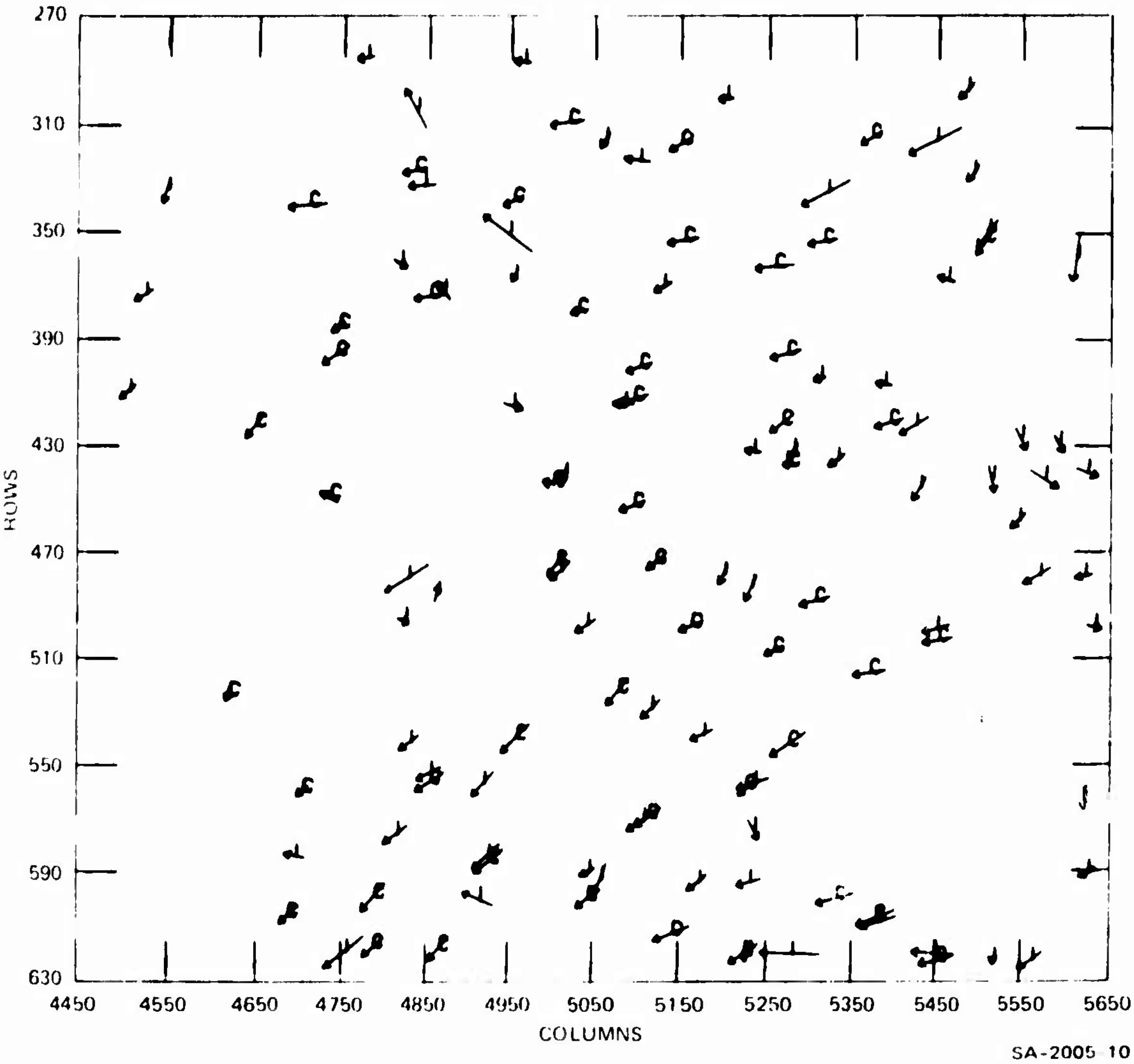

FIGURE 21 MOTION VECTORS BETWEEN FRAMES 4 AND 5, ATS-III, 23 AUGUST 1969

Vectors labeled "C" are measured on the ESIAC. Screened cloud motions, labeled "I," are from the Objective Cloud Tracking System.

Table 3

SUMMARY OF DIFFERENCES BETWEEN SCREENED COMPUTER-MEASURED CLOUD MOTIONS AND ESIAC-MEASURED CLOUD MOTIONS

	ΔU^*	ΔV^*	$\Delta\theta$	|Vector Difference|	|Difference in Magnitude|
Average	-0.352	-0.057	34.551	2.809	1.670
Range containing 68 percent of the differences	-2.1 to 1.9	-1.7 to 1.7	0.0 to 39.9	0.0 to 3.2	0.0 to 1.8
Standard deviation	2.86	2.03	32.68	2.12	1.79

*Units for U are columns divided by 3; units for V are rows.

difference, and the middle lines give the range containing 68 percent of the values (analogous to the plus/minus one standard deviation range of a normal variate), and the bottom line gives the standard deviation. Notice that in some cases the average difference, which is influenced by a few extreme values, lies outside the range containing 68 percent of the differences. The average magnitude of the cloud console motions is 3.03; the average magnitude of the motions determined by the computer is 3.07.

Several screening techniques have been applied to the motions calculated by the objective method:

- Tracers that did not persist over at least three frames were deleted.
- Motions that had lower confidence of being valid were deleted; i.e., the allowable changes in size, shape, and brightness were deleted.
- The motion vectors were clustered (using ISODATA); those classed as outliers were deleted.

It should be noted that screening is done intuitively by a man using visual aids (methods) like the ESIAC. In fact, this intuitive screening is one of the strong points of the visual interaction.

In some cases the same tracer was picked by both methods and tracked over several frames. For these tracers, there was good agreement in the CMVs for the tracers, much better than the average agreement reported in Table 3.

While the results of this comparison are encouraging, differences in magnitude of about one picture element or less had been a goal. It is evident from Table 3 that this goal was not achieved. One reason is the crudeness of the facsimile pictures, limiting the amount the pictures could be blown up on the ESIAC. For the blowup used, each ESIAC cursor unit was about one picture element. Since the cursor can be positioned only on integral values, about one picture element error may occur just in the placement of the cursor. Another reason is errors in the motions computed by the objective method. That there are errors is shown by the need to screen these motions. These errors arise from a cloud changing its shape slightly between a pair of frames. The objective method is not "smart" enough to use only that portion of the cloud that does not change. In an on-going project for NASA, Contract NAS5-20046 (SRI Project number 3320), some improvements in the clustering help to overcome this error.

Thus, this comparison should be repeated using better pictures, with the picture blown up so that cursor placement is not a problem. The human should try to identify each of the tracers selected by the objective method. Finally, this comparison should be extended to many other areas, including areas where more than one level of cloud motions are present, to try to determine the limits of the objective method. As these limits are found, new improvements should be made to raise the limits.

2. NOAA Automatic (Correlation) Versus SRI Objective (Clustering) Methods

Some ATS-I data were made available to us by Mr. Charles Novak of NOAA. The brightness observations are in the form of 64 by 64 element arrays originally selected to be located at 5° latitude-longitude intersections on the earth. In the cross-correlation computation, a 32 by 32 subarray from the center is selected on the first picture and is then located to give the best fit in the 64 by 64 data array taken from the second picture. The computed cloud motions were given in terms of row and column displacements and also in earth coordinates as cloud motion in speed and direction. Our computations were made also in row and column displacements for direct comparison with the NOAA values (in rows and columns).

The NOAA and SRI cloud motion vectors are shown in Figure 22. Each square represents a 64 by 64 area. While the vectors within the boxes are drawn to a 1:1 scale in position and magnified 2:1 in length, the location of the boxes serve only to indicate the relative longitude and latitude of its center. The distance between boxes is arbitrary. In the upper left square, the vector at the center of the rectangle, denoted N, shows the NOAA computation. The vectors marked A through E show SRI computations with A being of highest reliability and E lowest (as determined by the changes in size, shape, and brightness). These are based on the brightest points in the region and may lie anywhere within the region. In this particular rectangle, there were no bright clouds near the center; therefore, no SRI computations were made there. The SRI vectors may include clouds at different altitudes and also undoubtedly include a few bad vectors (not representative of an actual wind). The vector S is the average of the vectors A through E and is plotted in the center of the area. Other plots in Figure 22 are similar.

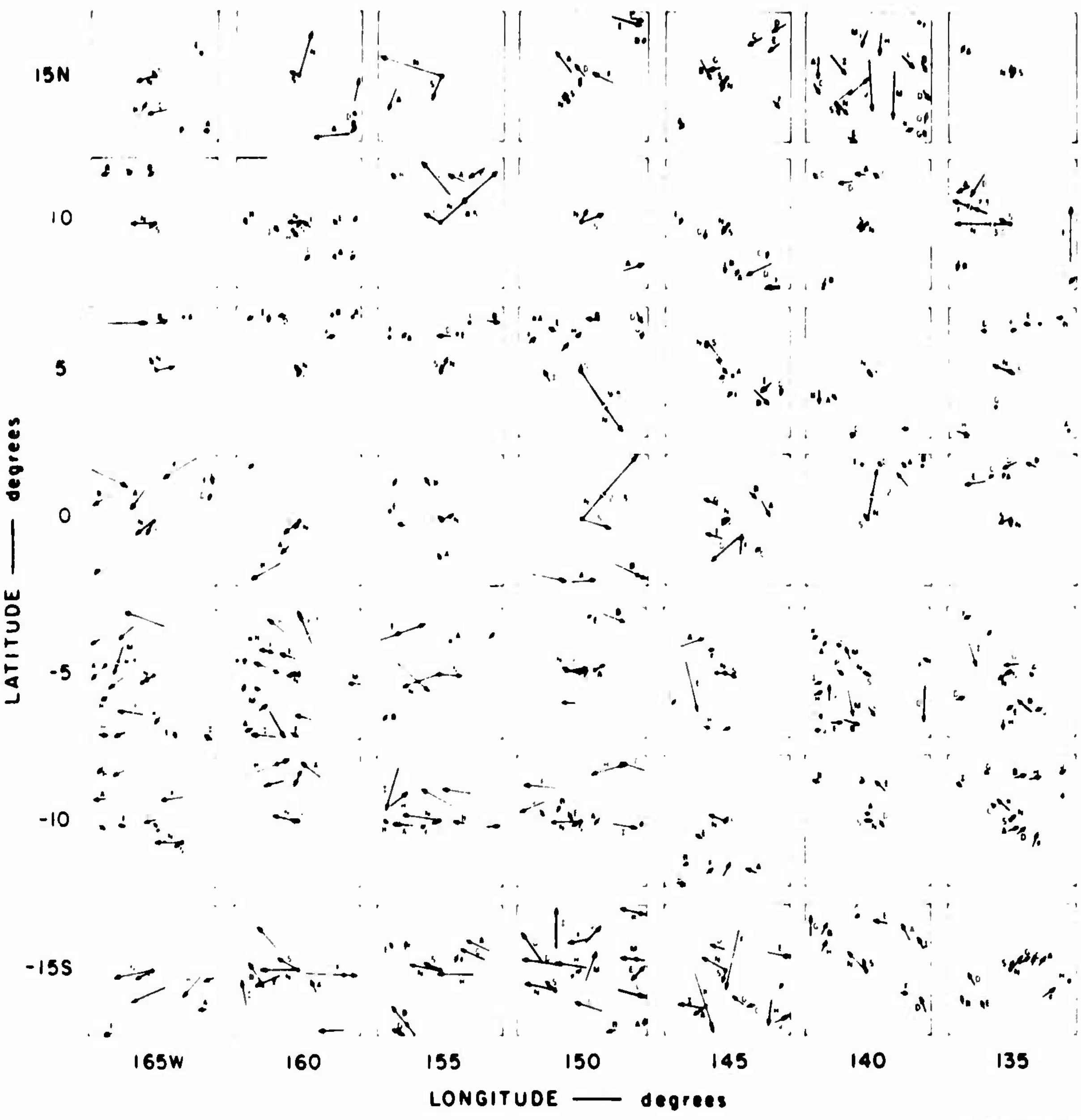

FIGURE 22 SRI (ISODATA) AND NOAA (CORRELATION) CLOUD MOTIONS FOR ATS-I DATA, 15 AUGUST 1972

The average SRI vector in each region and the NOAA vectors are plotted at the center of each box and labeled S and N, respectively. See text for a more complete description.

From the plots it is evident that one major difference is in the number of vectors in each area computed by the two methods. The NOAA method gets one vector, the SRI method gets many. For the 49 areas in this test, the SRI method got 335 vectors, or an average of 6.8 per area, with a minimum of 1 and a maximum of 16 per area.

Because of random distributions of the bright clouds, many of the SRI vectors fall near the edges of the rectangles. As mentioned earlier, edge problems are a major source of error. Ordinarily this problem is reduced by using larger data arrays and discarding vectors near the edge, but this was not feasible with these data. The average SRI vectors do not generally agree well with the NOAA vectors as can be seen from the Ns and Ss of Figure 22. With regard to the NOAA vectors, these have the obvious drawback of not being based on the brightest clouds in the area. As discussed earlier, a human analyst generally chooses bright targets and the results might differ significantly from the arbitrary locations selected by the NOAA technique. The single S vector at the center of each box is the average of all the SRI vectors within the box, without regard to possible differences in altitude of the individual vectors. Thus, it might not represent any actual wind. Of course, the large size of some of the NOAA vectors indicate probable errors.

The average difference between the mean SRI vector and the NOAA vector is given in Table 4. The range of 68 percent of the differences and the standard deviations are also given. The average magnitude of all the motions is about three picture elements.

This comparison shows major differences in CMVs computed for the same area by the two computational methods. It is important to note that either technique may be giving the correct motions. To resolve the question of the real cloud motion vectors, an independent determination should be made by human analysts using the entire picture sequence for

Table 4

AVERAGE DIFFERENCE BETWEEN MEASUREMENTS OF CLOUD MOTION VECTORS BY SRI OBJECTIVE (CLUSTERING) AND NOAA (CORRELATION) METHODS

	ΔU*	ΔV*	Magnitude of Vector Difference	$\lvert\Delta\theta\rvert$
Average difference	-0.62	0.88	4.3	67.2
Range containing 68 percent of the differences	3.5 to 2.3	-2.0 to 2.0	0 to 3.6	0 to 98.2
Standard deviation	4.75	4.37	4.9	49.0

*(In grid units.)

the day. Likewise, the comparison should begin in an area where only one level of motion is present before proceeding to more complicated areas.

Another way to compare computational methods is to use artificial data in which the motion vectors are known ideally by construction, so that each individual method can be compared to an ideal. Such a comparison of the SRI objective system and the ESIAC has been made on a project for the Navy.[27] In this case, there was good agreement between the SRI objective method (ISODATA) and the ESIAC.

In summary, the differences between NOAA and SRI cloud motion vectors are significant for this data and it is not possible from the available information to judge which set is preferable. However, from

[27] D. J. Hall, F. K. Tomlin, and D. E. Wolf, "Theory and Experiments on Automatic Cloud Tracking," Final Report, Contract N62306-71-C-0068, Stanford Research Institute, Menlo Park, California (November 1973).

our study for the Navy, we can see that the ISODATA system is in general agreement with human tracking for this ideal data. We hope to generate many more sets of ideal data to cover a wider range of possible data types, and thus approach a real-data situation.

D. Comparison of CMV Methods

A general description of the various CMV methods has been given previously. These methods are the film loop technique, the SRI cloud console technique, the correlation techniques (the NOAA approach and the University of Wisconsin approach), and the clustering technique (the SRI objective method).

The film loop technique is essentially an off-line operation as film needs to be produced. Anything that the film loop can do can be done better by the SRI cloud console technique. Thus, the film loop technique will be deleted from further consideration here.

This leaves the SRI cloud console as the only visual technique. The advantages of the visual technique are many, and to a large extent complement a computational method. A man viewing pictures in time lapse can get a tremendous amount of insight as to the cloud motions over a region, even when very complex motion is present. However, making detailed measurements on actual cloud tracers can become very tedious and time consuming. The computational methods do well with a single layer, fairly uniform flow of clouds. Thus, the cloud console can be used for measurements on clouds in the more complicated areas or for identifying multiple cloud layers in a region. Further improvements in the computational approaches and inclusion of infrared data will probably enable them to cope with more complicated areas, such as a two level wind, but there will always be areas, too complicated for a computational method, that

require a visual method. Also, the visual system could be used for final editing of the motions produced by the computational method.

As stated earlier, computational methods for CMVs are of two basic types: correlation and clustering. The two existing methods differ only in the method of selecting a tracer. As mentioned previously, one takes picture data from preselected grid points, the other uses a man to visually select the portion of a cloud that contains a cloud or portion of a cloud (tracer) that persists for several frames. Both methods of tracer selection have strengths and weaknesses. The first method is objective--it can be done entirely by a computer and the obtained motions are on a regular grid, which is a form compatible with existing forecasting techniques. However, there may be no clouds in the selected data or clouds may be partially obscured at one time and not at the other time, hence the computations would indicate an incorrect apparent motion. The other method uses a man to pick tracers that are reliable, however it ties him, and an expensive piece of hardware, to this tedious task of tracer selection. The motions obtained from this second method should be reliable, and not need as much editing as the other method.

Additionally, the following advantages and disadvantages are shared by the correlation methods.

- Advantages of correlation methods
  - These methods are relatively easy to apply. The correlation is computed between two sets of picture data for various placements of one set of the data in the other set. The location that gives the maximum correlation indicates the probable motion between the two sets of data.
  - A hardware device can be made to compute the correlation, thus greatly speeding up the computations.

- Disadvantages of correlation methods
  - Difficult to include additional information such as infrared data. The area included around the tracer might have many different infrared values (if the area is sufficiently complicated). Probably any computed motion would be an average of all motions present at the different heights; if a motion could be computed it might be meaningless to try to assign a height.
  - Difficult to threshold out background. Over a homogeneous background such as an ocean, this makes little difference. However land in the background would tend not to move (in fact should not move), thus at least blurring the peak correlation. In fact, clouds may be part of the background as in a two level cloud area in which winds (and clouds) are moving in directions different from each other at the different levels.

The other computational method is the SRI Objective Technique which uses clustering. Some of its advantages and disadvantages are as follows:

- Advantages of the clustering method
  - Relatively easy to include infrared data--or any additional information. At present, the clustering uses three variables or dimensions: positions x and y, and brightness. Inclusion of IR gives four variables. Clustering, at least in theory, is unlimited as to the number of dimensions; in practice, data sets with as many as 50 dimensions have been clustered using the ISODATA program. It is hoped that inclusion of IR data will enable the motions to be sorted into heights.
  - Can be used equally well over land or water. The separation of points that represent clouds from background is the first step in the clustering method. Only the points that represent clouds are used in the computations.
  - Can be adapted to different scales. Parameters exist within the clustering routine for controlling the minimum and maximum distances between brightness centers (tracers).

- Disadvantages of the clustering method
  - All of the computations must be done by software. It would be very costly to build a piece of hardware to carry out these computations. In fact, it would probably be cheaper to buy additional computers than to build the special purpose hardware.
  - In general the motion vectors computed by the clustering approach are scattered throughout the region being processed. In fact, they are placed at centers of brightness that are located in clouds, which occur almost randomly in a region. Some applications of the CMVs may require them to be on a regular grid; this grid would have to be filled in. (Note that the NOAA correlation method is set up to give CMVs on a regular grid.)
  - It is relatively complicated to develop. Many parameters are involved in the overall process, optimum values have not been found. Some will have to be changed for the inclusion of the IR data.

In conclusion, there are some serious limitations of the correlation methods that limit the types of applications they are suitable for. In theory the clustering method does not have these limitations, being limited only by the data. However, in practice, optimum values of the many parameters have not been found, thus limiting the current practical applications. A visual method is useful for getting motions in complicated areas and editing those motions obtained by the computational methods.

E. Registration and Gridding

Of prime importance in the use of data from a geosynchronous satellite are registration and gridding of the pictures. If the satellite's orbit were perfect, there would be no registration problem. However, such perfection is next to impossible to obtain, and if obtained would last for only a relatively short time. Errors in current and past geosynchronous orbits have been observed to be large enough to cause motions to look like they were going the wrong way. The gridding problem consists in

converting to geographic coordinates. Unless this step is accomplished, any measurements made on the pictures or on the digital data ·ould be left in almost meaningless arbitrary picture coordinates.

There are two uses of registration data: (1) the pictures or portions of pictures viewed on a display device need to be corrected to the point that remaining distortions in the pictures do not destroy or influence the apparent meteorology of the region, and (2) corrections need to be made to the cloud motion vectors. Remaining errors at this stage are a bias and may adversely affect the application of the CMVs.

It is assumed that the pictures will be stored digitally within the system, and any corrections will be made to the digital data as they are read from main memory and transferred to the display device. As rotations and magnifications are next to impossible to perform in a reasonable amount of time in digital data, corrections to the pictures used on the display device will consist of a translation. While this simple correction cannot hope to get rid of all the errors, at least the remaining errors will not influence the meteorology of the region being viewed. For smaller areas, the simple translation is a better approximation for error corrections. In larger areas, the global flow patterns are of most importance; they are not as affected by the smaller scale errors.

It has been assumed in the SRI objective cloud motion computation system that only the final product, the cloud motion vectors, need be registered. In this manner, these corrections need to be applied to a relatively few vectors, not to the tremendous quantities of actual picture data. This should consist in subtracting the vector component due to satellite orbital error from each apparent cloud motion, depending on the location of the apparent motion. Any system capable of producing error motions at any arbitrary location could supply a translation for the pictorial purpose.

SMS specifications call for a gridding bit to be included with the stretched signal. The inclusion of such information, if it can be relied on, would be a big help. In the absence of information on how to make use of this information and the strong doubts as to its reliabilities, two other methods have been attempted. Neither of these methods rely on knowledge of the orbital parameters. Both rely on landmark matching, i.e., finding the location of known landmarks in successive frames of data using a template matching procedure. Also, knowing the location of these landmarks in the data and the geographic coordinates enables the gridding to be done.

One registration and gridding method was developed by Roy Endlich at SRI[28] and uses an iterative approach to calculate a correction including translation, rotation, and magnification to allow the landmarks from one picture to overlay the landmarks in the next picture as closely as possible.

Another registration method was developed by Dr. A. R. Tobey[29] at SRI. In it, the error motions are represented by Fourier series. Coefficients of the Fourier series terms are functions of earth or picture coordinates. Two-dimensional Taylor series are used to express this spatial dependence of the Fourier coefficients. Thus the computation of apparent motions for any given picture location is a simple series evaluation. The series coefficients are determined from the landmark registration data using least squares.

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[28] D. E. Wolf, R. M. Endlich, and D. J. Hall, "Further Development of Objective Methods for Registering Landmarks and Determining Cloud Motions from Satellite Data," Scientific Report, U.S. Navy Contract N62306-71-C-0068, pp. 51-59, Stanford Research Institute, Menlo Park, California (September 1972).

[29] D. E. Wolf, D. J. Hall, A. R. Tobey, and R. G. Hadfield, "Development of an Automatic Computer System for Measuring Cloud Motion Vectors," Final Report, NASA Contract NAS5-21776, pp. 13-22, Stanford Research Institute, Menlo Park, California (September 1973).

At this stage of development, both methods appear promising. Much more testing with real data is needed to determine the preferable method.

F. Identification of Problem Areas and Future Work

1. Comparisons

The comparisons summarized in this report should be extended to a three-way comparison between the Correlation technique, the SRI Objective technique and the ESIAC. The facsimile pictures used for the ESIAC-SRI Objective comparison are barely adequate. A far better comparison will result when the planned digital input for the ESIAC is achieved. The SRI Objective-Correlation comparison was hampered by lack of visual data for verifying the computed motions and by the use of only two frames of data. Finally, many areas should be covered in the comparisons to try to identify the types of areas best for each system and the limitations of each system.

2. Registration and Gridding

As stated earlier, two prototype systems were proposed to handle the registration and gridding. Neither system is fully developed. In addition, NOAA and University of Wisconsin have systems that are attempts to solve this problem. All of these systems should be explored and tested with actual data to find a dependable registration and gridding system. Development of such a system is of utmost importance to a Meteorological Information System using satellite data.

3. Improvements to CMV Analysis Algorithms

At least one reason for making comparisons of the CMV systems is to identify problem areas so they can be corrected and the overall systems improved. As stated earlier, the computational methods can

compute valid motions in a single level wind area. Tests with the SRI Objective Method show that improvements are necessary before a more complicated area can be solved. A tentative improvement that seems to help in a two-level wind case is to sum two consecutive pictures before applying the Objective Method.[30] Further exploration of this and possibly other improvements is necessary.

Some assessment of the value of including infrared (IR) measurements for CMV analysis is necessary as soon as these data are available. Limited tests have been made using the SRI Objective System on one frame of NOAA-2 data (with both visual and IR channels). These data were clustered using the ISODATA program; the brightness centers produced appeared reasonable and some were separated primarily by height. No CMVs could be computed as the data consisted of only one frame. Simulated IR measurements were included with the artificial data generated in the study for the Navy[31] mentioned previously. The SRI Objective System used three IR values in addition to visual data values to compute CMVs that were virtually identical with the specified data, as were CMVs measured on the ESIAC. These results were obtained even though a very complicated area was simulated. However, several simplifying conditions were met, such as not allowing clouds to partially obscure each other.

Even assuming that IR data, are useful for CMV analysis, a problem exists in implying the CMV height from the IR temperature. Some clouds, such as high cirrus, are too thin to have much influence on the

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[30] D. E. Wolf, D. J. Hall, A. R. Tobey, and R. G. Hadfield, "Development of an Automatic Computer System for Measuring Cloud Motion Vectors," Final Report, NASA Contract NAS5-21776, pp. 31-32, Stanford Research Institute, Menlo Park, California (September 1973).

[31] D. J. Hall, F. K. Tomlin, and D. E. Wolf, "Theory and Experiments on Automatic Cloud Tracking," Final Report, Contract N62306-71-C-0068, Stanford Research Institute, Menlo Park, California (November 1973).

IR channel, thus the height would be much too low. For another case, the IR temperature of a tall cumulus cloud is a cloud top temperature, whereas the motion derived from such a cloud seems to be more representative of the base of the cloud. This problem has been discussed in the task on radiometry.

4. Obtaining Motions in Cloud-Free Areas

Cloud motions are measured from satellite data to estimate winds in the absence of actual wind measurements. One method that might be used in the tropics has been proposed by Endlich, Mancuso, and Nagle.[32] Briefly, the idea consists in tracking humidity patterns on an isentropic surface in much the same manner as used to track clouds. Some experiments on tracking simulated humidity patterns are described in Mancuso and Wolf.[33] Another method would be to compute geostrophic winds from retrieved temperature profiles. Both of these methods need to be explored to be assured of getting estimates of winds in any area of interest.

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[32] R. M. Endlich, R. L. Mancuso, and R. E. Nagle, "A Proposed Method for Determining Winds in Cloud Free Regions by Isentropic Analysis of Temperature and Water Vapor Profiles," J. Appl. Meteor., Vol. II, No. 6, pp. 1019-1021 (September 1972).

[33] R. L. Mancuso and D. E. Wolf, "Numerical Procedures for Analyzing and Predicting Mesoscale Tropical Weather Patterns," Final Report, U.S. Army Contract DAHC04-71-C-0013, pp. 33-41, Stanford Research Institute, Menlo Park, California (January 1974).

V ANALYSIS AND FORECASTING SOFTWARE REQUIREMENTS

A. Introduction

A flow diagram of proposed software for the MIS is shown in Table 5. Computer programs that could be u ' and that are currently available at SRI are noted in parentheses; however, they would need to be modified for use in a small-word computer. In this flow diagram, it has been assumed that the system is fully automated, except for the diagnosis and neph-analysis. However, the operator would be able to exercise considerable control, particularly over the input and output data using light-pen CRT unit. Also, the software would be designed so that the operator could request a wide variety of analysis and forecasting options with the teletype.

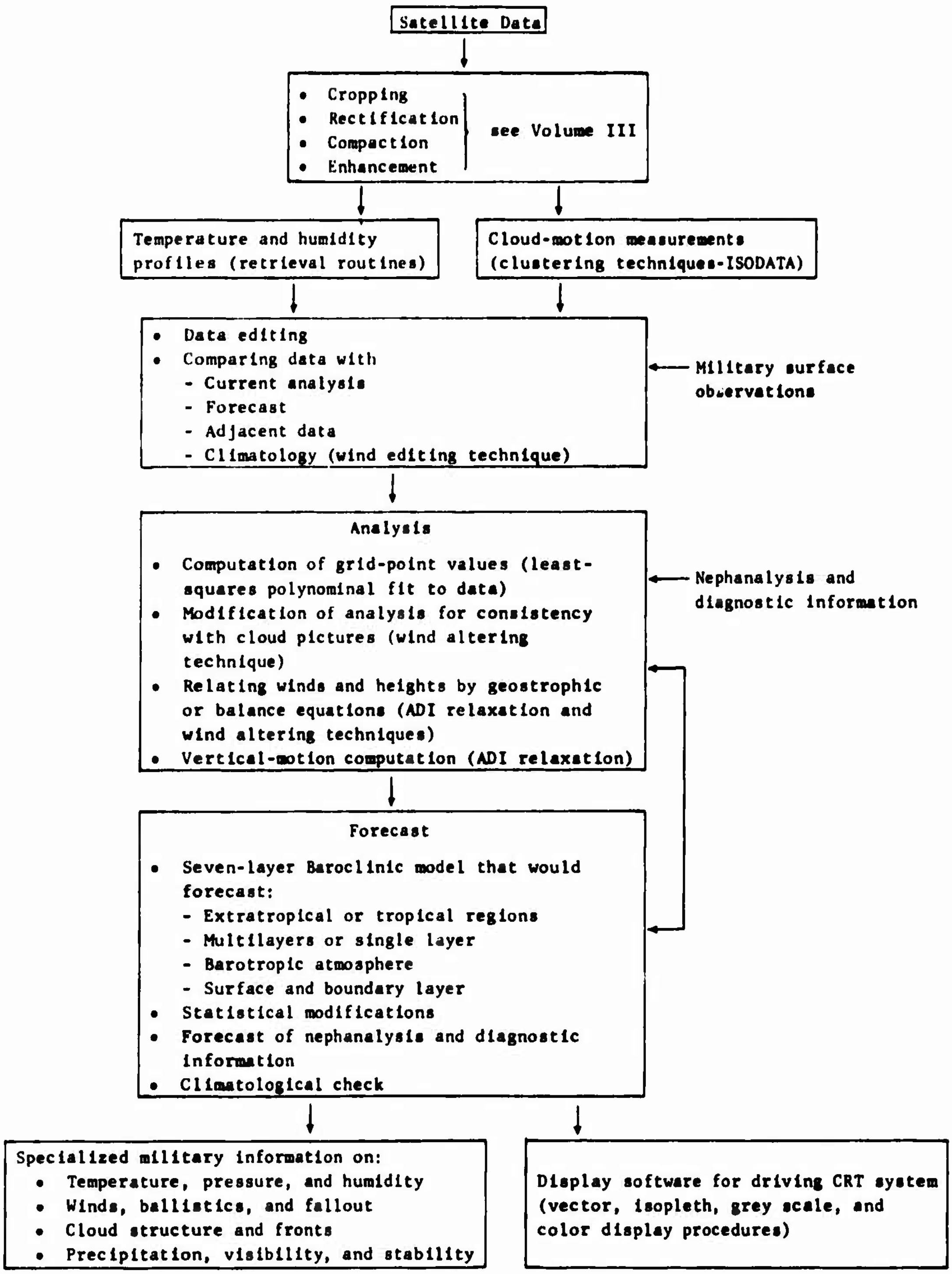
B. Satellite Data Requirements

Forecasting in extratropical regions has generally been based on height fields of constant pressure surfaces. This has been principally due to the availability of this type of data and because the wind field can be derived from the height field by using eitner the geostrophic or the balance relationship. The satellite data that would be most suitable for use in extratropical forecasting are the temperature profiles supplemented by cloud motions. Current problem areas associated with using theses data are:

- Reference pressure heights for constructing pressure height profiles.
- Temperature profile accuracy over land areas where there is no surface temperature data.

Table 5

PROPOSED FLOWCHART OF MIS SOFTWARE



- Physical interpretation of cloud motions and cloud-motion heights.
- Atmospheric structure below clouds.

Many of these problems should be resolved by the late 1970s; for example, reference pressure heights could be obtained using a two-satellite microwave occultation system.[34] Other types of data that might be derivable from satellite measurement and that would certainly be useful in a forecasting scheme are:

- Humidity profiles or the total precipitable water content
- Cloud amount, including height and thickness
- Precipitation and fog
- Information about fronts, squall lines, and tornadoes.

In tropical regions, the emphasis has always been placed on wind data; this is due to the weak horizontal temperature gradients and the lack of a geostrophic relationship. Currently, MIS forecasting in tropical regions would have to be based almost entirely on the measurement of cloud motions from satellite photographs. However, this type of data does not provide a complete coverage and would need to be supplemented by other data. Possible additional sources for tropical data are:

- Isentropic motions in clear air[35]
- Density profiles[36]

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[34] S. G. Ungar and B. B. Lusignan, "Analysis of Ground Test of a Microwave, Earth-Occultation, Pressure-Reference-Level System," J. Appl. Meteor., Vol. 12, No. 5, pp. 874-881 (August 1973).

[35] R. M. Endlich, R. L. Mancuso, and R. E. Nagle, "A Proposed Method for Determining Winds in Cloud-Free Regions by Isentropic Analysis of Temperature and Water Vapor Profiles," J. Appl. Meteor., Vol. II, No. 6, pp. 1019-1021 (September 1972).

[36] B. B. Lusignan, "A Preliminary Study of Atmospheric Density Measurements by Means of Satellite," Final Report, Contract NAS 9-7020, Stanford University, Stanford, California (1968).

- Constant-level ballons[37]
- Temperature profiles (Section III).

C. Data Preparation and Editing

Data preparation consists of cropping, rectification, compaction, enhancement, profile retrieval, and cloud-motion measurements. Discussions of these steps and the software requirements are given in other sections of the report. The data editing consists principally of removing erroneous data. Automated checking of data for bad values can be performed by comparing individual datum with the most recent analysis, adjacent measurements, forecast values, and climatology.[38] It is doubtful that a fully automated editing would be completely satisfactory. On the other hand, a manual checking of all the data would be impractical. Thus, a hybrid system seems best, where a man would use the CRT display to check and control the automatic editing. Numerous schemes for computing grid-point values have been developed; the most successful of these have been those of Bergthorsson and Doos,[39] Barnes,[40] and Endlich and Mancuso.[41]

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[37] P. Morel and W. Bandeen, "The EOLE Experiment--Early Results and Current Objectives," Bull. Amer. Meteor. Soc., Vol. 54, No. 4, pp. 298-306 (April 1973).

[38] R. M. Endlich, R. L. Mancuso, H. Shigeishi, and R. E. Nagle, "Computation of Upper Troposphere Reference Heights from Winds for use with Vertical Temperature Profile Observations," Mon. Wea. Rev., Vol. 100, No. 11, pp. 808-816 (November 1972).

[39] P. Bergthorsson and B. R. Doos, "Numerical Weather Map Analysis," Tellus, Vol. 7, No. 3, pp. 329-340 (1955).

[40] S. Barnes, "A Technique for Maximizing Details in Numerical Weather Map Analysis," J. Appl. Meteor., Vol. 3, No. 4, pp. 396-409 (August 1964).

[41] R. M. Endlich and R. L. Mancuso, "Objective Analysis of Environmental Conditions Associated with Severe Thunderstorms and Tornadoes," Mon. Wea. Rev., Vol. 96, No. 6, pp. 342-350 (June 1968).

More complex schemes have not given better results due to measurement errors and uneven distributions of data.*

D. Analysis

The analysis area and grid for the MIS system should cover a large enough area to include all weather that might reach the area of military interest over a 48-hour forecast period. A possible grid system is shown in Figure 23. In this figure, it is assumed that the battle is taking place in midlatitudes (westerly flow), thus, the center of the grid is displaced to the west of the battlefield. In the tropics, it would probably be best to center the grid directly over the field. Various other area configurations and networks could be used including ones that permit orientation of the grid with the upwind direction and ones suitable for the polar regions. Grid points spacing in equal degrees of latitude and longitude have been used in Figure 23, since this type of grid (spherical) is convenient. The grid shown has points spaced every 1° latitude and longitude. There are a total of 2,601 points within the entire grid and 9 points lie within the area of military activity. If a 2° grid spacing is used, then the total number of points is reduced to 676; however, this would not show any detail of the weather within the critical area.

Currently, temperature-profile data from satellites can be used to produce analyses that depict the general atmospheric flow patterns. With planned improvements in instrumentation and profile retrieval techniques, the data will portray detailed jet-stream features to a horizontal

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* Y. Ramanathan, P. Kulkarni, and D. R. Sikka, "A Comparative Study of Fourier Analysis Procedures and Cressman's Method in Objective Analysis of the Wind Field," J. Appl. Meteor., Vol. 11, No. 8, pp. 1318-1321 (December 1972).

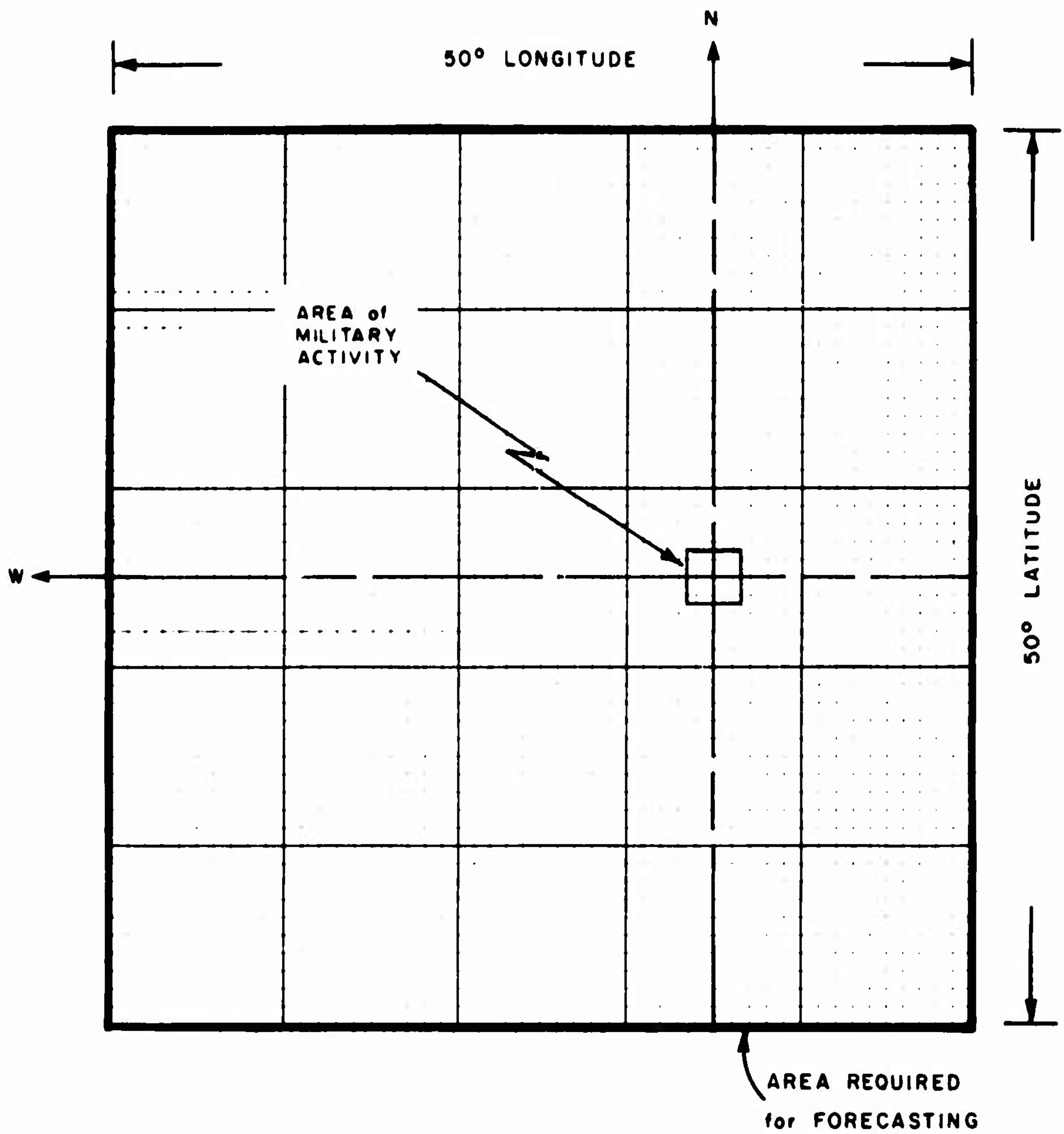

FIGURE 23 POSSIBLE MIS FORECASTING GRID

resolution of about 2 degrees latitude.[43] With additional improvements in instrumentation and by restricting the radiometer scanning to cover only the relevant area, an even greater resolution is possible. However, a horizontal resolution of about 1° and a vertical resolution of seven layers would be about the best that could be obtained with current technology. This is due principally to the limitation in the accuracy and the vertical resolution that can be achieved using profile retrieval techniques (see Section III). In addition, the generation of even 2,601 temperature retrievals will take an excessive amount of time unless multiple processing is performed. Thus, a more practical approach might be to produce fewer temperature profiles in regions that portray a high degree of uniformity and in the regions that are more distant from the battlefield.

A very high horizontal resolution information would be obtained from cloud imagery and other satellite data including cloud-motions measurements. This type of information could be analyzed to a much greater detail using a more dense grid spacing ($<<1^\circ$), when over the immediate area of military conflict.

The analysis program should have the capability of going from winds to heights and back, and of computing a stream-function field from winds. Also, it should be able to generate a vertical-motion field using the omega equation. Various techniques are available for achieving the above, and those developed at SRI have been documented.[44,45]

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[43] W. E. Togstad and L. H. Horn, "An Application of the Satellite Indirect Sounding Technique in Describing the Hyperbaroclinic Zone of a Jet Streak," J. Appl. Meteor., Vol. 13, No. 2, pp. 267-276 (March 1974).

[44] R. L. Mancuso and R. M. Endlich, "Wind Editing and Analysis Program--Spherical Grid (WEAP-1A)," User's Manual, Contract DAHC04-71-C-0013, Stanford Research Institute, Menlo Park, California (February 1973).

[45] R. L. Mancuso, "Computer Routines for Relaxation and Analysis," Final Report, Contract 3-35263, Stanford Research Institute, Menlo Park, California (May 1974).

Weather patterns as portrayed by satellite imagery can also be used to provide additional meteorological information as described by Nagle et al.,[46] Sikdar and Suomi,[47] and Steranka et al.[48] This type of objective can be used to modify the objective analyses. Also, it may be desirable to add new off-time data to improve existing analyses. Modifications can be made by using either the light pen or the teletype to input the information. The analysis can be modified directly or by using techniques, such as the vector separation method of Endlich.[49]

E. Forecasting Models

Primitive-Equation (PE) forecasting models have been developed to such a high degree that they take into account almost all effects in the atmosphere.[50] With these complete models it is possible to provide predictions of all quantities including heights, temperature, winds, humidity, cloud amount, precipitation, and various weather phenomena. Such models require very fast computers with large memories. If a sufficiently complex

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[46] R. E. Nagle and C. M. Hayden, "The Use of Satellite-Observed Cloud Patterns in Northern-Hemisphere 500-mb Numerical Analysis," NOAA Tech. Rep. NESS55, National Oceanic and Atmospheric Administration, Washington, D.C. (April 1971).

[47] D. N. Sikdar and V. E. Suomi, "On the Remote Sensing of Mesoscale Tropical Convection Intensity from a Geostationary Satellite," J. App. Meteor., Vol. 11, No. 1, pp. 37-43 (January 1972).

[48] J. Steranka, L. J. Allison, and V. V. Salmonson, "Application of Nimbus 4 THIR 6.7 μm Observations to Regional and Global Moisture and Wind Field Analyses," J. Appl. Meteor., Vol. 12, No. 2, pp. 386-395 (March 1973).

[49] R. M. Endlich, "Direct Separation of Two-Dimensional Vector Fields into Irrotational and Solenoidal Parts," J. Math. Anal. Appl., Vol. 33, No. 2, pp. 328-334 (February 1971).

[50] G. J. Haltiner, Numerical Weather Prediction (John Wiley and Sons, Inc., New York, N.Y., 1971).

computer system is used for MIS, then models such as Krishnamurt et al.[21] or Kaplan et al.[22] might be adapted to the MIS system. However, a less complex scheme based on the Baroclinic model concept could be more easily adapted to a small minicomputer facility and would probably be more suitable for the initial MIS system.

It is important in the MIS mesoscale model that more accurate finite-difference treatments be used in order that the details in the initial fields be preserved.

Conventional forecasting models have been formulated for treating relatively large-scale phenomena of wavelengths 10 times the grid spacing. The models could be applied to smaller scales by simply reducing the grid spacing; however, this would be very inefficient compared to developing more accurate interpolation schemes.[23,24,25]

The forecasting model developed for the MIS should be sufficiently flexible so that it could be used in tropical regions where it would be

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[21] T. N. Krishnamurti, M. Kanamitsu, B. Ceselski, and M. B. Mathur, "Florida State University's Tropical Prediction Model," Tellus, Vol. XXV, No. 6, pp. 523-535 (1973).

[22] M. L. Kaplan, R. M. Cowher, and R. J. Gronek, "The Proposed AFGWC Operational Mesoscale Primitive Equation Forecast Model," Fifth Conference on Weather Forecasting and Analysis, 4-7 March 1974, American Meteorological Society, Boston, Massachusetts, pp. 113-116 (1974).

[23] M. B. Mathur, "A Note on an Improved Quasi-Lagrangian Advection Scheme for Primitive Equations," Mon. Wea. Rev., Vol. 98, No. 3, pp. 214-219 (March 1970).

[24] J. P. Gerrity, Jr., R. D. McPherson, and P. D. Polyer, "On the Efficient Reduction of Truncation Error in Numerical Weather Prediction Models," Mon. Wea. Rev., Vol. 100, No. 8, pp. 637-643 (August 1972).

[25] R. L. Mancuso and D. E. Wolf, "Numerical Procedures for Analyzing and Predicting Mesoscale Tropical Weather Patterns," Final Report, Contract DAHC04-71-C-0013, Stanford Research Institute, Menlo Park, California (January 1974).

based principally on wind data and would emphasize phenomena such as convection. The area and grid configurations and number of layers that are used in the model should be variable and controllable by the operator. In addition to providing multilayer forecast, the model should be able to provide simpler forms of forecast if requested by the operator, such as:

- Barotropic forecast.
- Surface forecast, similar to Reed's model
- Single-layer upper-air forecast
- Persistence and climatology forecast, particularly for use in the tropics if input data is insufficient.

It will be necessary to forecast quantities such as cloud amount, precipitation, fronts, and other information provided by the nephanalysis and diagnosis. Techniques similar to those of Collins could be used to provide prognosis of these phenomena. An approach that might be very suitable for the MIS system would be to determine the future locations of various features such as fronts by moving them identically with the forecast of constant-pressure height and temperature patterns. This could be accomplished by recognizing and tracking the movements of the forecast patterns using a pattern recognition technique such as that developed by Hall and Wolf (Section IV).

R. M. Endlich and R. L. Mancuso, "A Multilayer Numerical Prediction Model for Investigating Tropical Weather Systems," Scientific Report, Contract DAHC04-71-C-0013, Stanford Research Institute, Menlo Park, California (October 1972).

R. J. Reed, "A Graphical Method for Preparing 1000-Millibar Prognostic Charts," J. Appl. Meteor., Vol. 14, No. 1, pp. 65-70 (February 1957).

R. W. Collins, "AFGWC Multilevel Cloud Model," AFGWC Tech. Mem. 70-10, Air Force Global Weather Central, Offutt AFB, Nebraska (December 1970).

R. W. Collins and A. R. Coburn, "Application of Satellite Data to an Automated Nephanalysis and Forecasting Program," in Automated Weather Support (Proc. 6th AWS Technical Exchange Conference, 21-24 September 1970), Tech. Rep. 242, U.S. Air Force, pp. 248-260 (April 1971).

Forecasting of severe storms would require special treatment with regard to forecasting conditions that are favorable for severe storms and tornadoes.[2,3,4] It is particularly important that the MIS system be able to provide an accurate analysis and portrayal of current conditions and of the quantities that permit recognition of severe-storm phenomena. Hurricane forecasting would also need individual treatment and statistical routines will be needed to:

- Include influence of mountains, convection, and diurnal variations in models.
- Produce statistical forecast of required weather from model parameter.[4]
- Generate yes/no and worded replies.

F. Computer Requirements

The computational times and program storage requirements for analyzing, forecasting, and displaying weather data on a CDC 6400 computer are given in Table 6. Conversion to various minicomputer systems are considered in Volume II. The computational times per layer are given for grids with spacings of 1° and 2° (2601 and 676 points, respectively). These results are either for actual computer runs or are estimates based on actual runs. Also, they are representative of the most accurate numerical

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[2] R. C. Miller and A. Bidner, "The Use of Computer Products in Severe-Weather Forecasting," in Automated Weather Support (Proc. 6th AWS Technical Exchange Conference, 21-24 September 1970), Tech. Rep. 242, U.S. Air Force, pp. 224-228 (April 1971).

[3] R. M. Reap, "Thunderstorm and Severe Weather Probabilities Based on Model Output Statistics," Fifth Conference on Weather Forecasting and Analysis, 4-7 March 1974, American Meteorological Society, Boston, Massachusetts, pp. 113-116 (1974).

[4] H. R. Glahn and D. A. Lowry, "The Use of Model Output Statistics (MOS) in Objective Weather Forecasting," J. Appl. Meteor., Vol. 11, No. 8, pp. 1203-1211 (December 1972).

Table 6

COMPUTATIONAL TIMES AND STORAGE REQUIREMENTS
ON A CDC 6400 FOR ANALYSIS AND FORECASTING SOFTWARE

Programs	Program Storage Requirements* (number of words)	Computer Time per Layer (sec) Grid Spacing	
		1°	2°
Editing			
Editing	1,000	156	41
Analysis			
Grid point	1,000	52	14
Wind alteration	250	7.8	2.0
Relaxation			
Stream function	850	7.8	2.0
Balance height	850	7.8	2.0
Omega equation			
Complete analysis program (initialization)	2,500	83	22
Forecast (48 hours)			
Advection	500	312	40
Surface (Reed's model)	700	312	40
Barotropic	1,500	780	102
Baroclinic			
Excluding vertical motion	1,500	780	102
Including vertical motion	2,000	1,248	162
Complex baroclinic	≥2,500	≥1,560	≥202
Primative equation	≥2,000	≥3,746	≥486
Display			
Basic plot routines	2,000	--	--
Vectors	150	7.8	2.0
Isopleth	700	2.0	2.0
Gray scale	2,200	12	12

*Excludes data storage requirements (see Table 7).

techniques that are currently available and of programs that have been constructed to minimize both the computer time and program size. (The computational times, however, for the data editing could be reduced considerably by developing a more efficient scheme.)

Computer requirements are given in Table 6 for varying complexities of forecasting models. The computer times given are conservative in that they assume that the computations must be performed at all of the grid points throughout the entire forecast period. However, since a forecast is only required within a relatively small central section of the grid (see Figure 23), the grid size could be continuously reduced throughout the forecast period. This would reduce the computation times to about 1/2 those listed in Table 6.

Only the minimum computer times and program sizes are given in Table 6 for the complex Baroclinic and PE models, since models of ever increasing complexity can be programmed. As can be seen, a PE model would require a considerable amount of computer time. Using Table 6, a 24-hour, seven-layer PE model forecast would take over seven hours on a CDC 6400. Such a model could also use considerable memory. For example, the five-layer PE model of the U.S. Navy** uses two CDC 6500* computers in addition to extended core storage, and even greater capacity is needed.

The data storage requirements for forecasting models are shown in Table 7 as a function of the grid spacing and number of arrays. Although three data arrays could possibly be worked with, it would be desirable to have six or even more. If six data arrays and a 2° grid spacing are

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**P. G. Kesel and F. J. Winninghoff, "The Fleet Numerical Weather Central Operational Primitive-Equation Model," Mon. Wea. Rev., Vol. 100, No. 5, pp. 360-373 (May 1972).

*A CDC 6500 has a dual-central processor, but otherwise it is equivalent to a CDC 6400.

Table 7

GRID DATA STORAGE REQUIREMENTS
(Per Layer)

Number of Arrays	Spacing of Grid	
	1°	2°
1	2,601	676
3	7,803	2,028
6	15,606	4,056

used, then the computer memory requirements for data would be 4,056 words (storage space for the program would also be needed). This assumes that only one atmospheric layer would be contained in the internal computer core storage at any given time, which would require frequent interchange between the internal and external storages. If the N layers are treated simultaneously within the computer, then the word storage requirements for data become $\geq N \times 4{,}056$. For a 1° grid spacing, the data storage requirements for one layer increases to 15,606 words.

G. Recommendations for Future Research

Research on mesoscale forecasting has been hindered due to the lack of upper-air observational data. However, recent data, such as that from the severe storm observational programs[64] should permit testing of various mesoscale model concepts. To develop an effective MIS forecasting model, investigations are needed with regard to:

- Improvements in the accuracies of finite-difference formulations and techniques.

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[64] S. L. Barnes, J. H. Henderson, and R. J. Ketchum, "Rawinsonde Observation and Processing Techniques at the National Severe Storms Laboratory," NOAA Tech. Mem., ERL NSSL-53, NSSL, Norman, Oklahoma, 246 pp. (April 1971).

- Comparison of Baroclinic and Primitive Equation models (this should also include comparisons with simple advection and statistical schemes).
- Significance and techniques of including effects such as friction, convection, and condensation.

Meteorological satellite data also provide an excellent source for developing and testing the MIS forecasting model. Current satellite data are still difficult to work with and their accuracies permit only large-scale analyses. However, very meaningful investigations can still be carried out by combining both temperature-profile data from NOAA-2 and cloud-motion data from the SMS. The effectiveness of different schemes could be tested for providing pressure-reference heights and cloud-motion heights, and for estimating the structure beneath clouds. Such tests would best be made over the United States where verifying observations are also available. At the present, temperature profiles are being provided only by polar-orbiting satellites. When these temperature profile data also become available from synchronous satellites, then completely independent sets of data and analyses will be produced at short-time intervals of about an hour. With this capability, new approaches to forecasting become possible, for example:

- Determine the divergence field that produces according to the vorticity equation the most recently observed one-hour change in the vorticity field. Use this computed divergence field as part of the initial conditions for a forecast.
- Determine the velocities of the movements of weather systems using pattern-recognition techniques. Use these velocities to move the systems and associated weather forward in time to produce a prognosis.

VI RECOMMENDED FOLLOW-ON WORK

A. Objective

It is suggested that follow-on work be undertaken. The objective of this proposed follow-on work would be to examine the meteorological capability, technical practicality, and military advisability of the MIS. As a result of this effort, WSMR would be able to establish performance requirements, design specifications, and logistic implementation of the proposed MIS.

The specific objectives of the follow-on work are:

(1) Meteorological Capability

The objective of this task is to determine the capability of the proposed MIS to provide militarily significant meteorological data. In particular, the limitations of a satellite-based weather analysis, the reliability of computer weather forecasts, and the degree of man-machine interaction need to be assessed. Finally, performance requirements will have to be generated for the proposed MIS.

(2) Technical Practicality

The objective of this task is to further evaluate the initial design specifications. In particular, efforts will be made to determine whether or not initial expectations of MIS practicality are warranted. This study will provide a basis upon which to accept or amend the initial design specifications.

(3) Military Utility

The objective of this task is to determine (1) the role of the proposed MIS in the military function, and (2) the logistics of integrating such a system into military operations. In particular, the need for digested status-and-forecast information, the importance of an on-site meteorologist, and

the vulnerability of the DMS and BMS vans to military attack need to be investigated. Finally, scenarios should be developed to show how commanders will make use of MIS data.

B. Approach to Follow-On Work

The proposed follow-on work is to be accomplished by: assembling a research prototype, developing support software, and evaluating meteorological performance.

1. Hardware Assembly

The research prototype will represent a breadboard version of this proposed MIS. It will allow:

- Evaluation of the MIS analysis and forecast procedure using actual satellite data.
- Determination of performance requirements for the proposed MIS.
- Determination of design specifications for the proposed MIS.

The research prototype will consist of a high-speed, small-word minicomputer, some core memory, a picture disc file, a tape drive, a teletype, and a light-pen CRT display. SMS data will be inputted from magnetic tape to the minicomputer, which in turn will store it on the disc file. Similarly, radiometric data will be inputted from polar-orbiting satellites. Rectification, cropping, compaction, and enhancement experiments will be performed using the disc file minicomputer and CRT display.

2. Software Development

To support the research prototype, software will be installed for carrying out: (a) radiometric analyses, (b) CMV measurements, (c) nephanalyses, (d) weather diagnosis, (e) weather prognosis, (f) data

reduction, and (g) data display. Currently, software exists for supporting the radiometric analyses, the CMV measurements (both cluster analysis and cross correlation), weather prognosis, data reduction, and data display. These algorithms can be installed on the research prototype without excessive labor.

Algorithms for supporting a man-machine nephanalyses diagnosis will be developed during the first phase of the proposed work and installed on the research prototype during the second phase. These programs, being interactive in nature, require considerable skill to design and construct. In particular, they involve complex peripheral operations (light-pen, CRT displays, keyboard input/output). Accordingly, considerable professional support will be needed to realize, install, and debug such algorithms.

3. Meteorological Evaluation

Following assembly of the research prototype and installation of the requisite software, meteorological experiments will be performed with real SMS data. The objective of such experiments is to evaluate the expected performance of the proposed MIS and to determine possible design specifications for a deployed system. In particular, semiautomatic radiometric and CMV analyses will be attempted.

In addition, using the light pen and keyboard, nephanalysis will be performed and the results displayed on the CRT. Weather diagnoses and prognoses will follow. Finally, weather-symbol maps and daily weather forecasts will be attempted. The results of these efforts will be compared with actual weather conditions and appropriate modifications made to the analysis procedure and processing algorithms.

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